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ICEBREAKER DESIGN SYNTHESIS  
ANALYSIS OF CONTEMPORARY  
ICEBREAKER PERFORMANCE

Prepared for:  
Transportation Development Centre  
Policy and Coordination Group  
Transport Canada

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by

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The contents of this report reflect the views of the contractor and not necessarily the official views or policies of Transport Canada

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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| 16. Résumé<br><p>Ce rapport fait le point sur l'état de la technologie des brise-glace, sept en tout, exploités par les compagnies pétrolières actives dans la mer de Beaufort. Ces sept navires présentent chacun des caractéristiques qu'aucun autre brise-glace de construction antérieure ne possède.</p> <p>Les capitaines de cinq de ces brise-glace ont été interrogés sur les performances de leur navire dans les rôles pour lesquels ils ont été conçus.</p> <p>Les chercheurs ont analysés les données d'exploitation et caractéristiques en vraie grandeur de ces navires, puis ils en ont comparé les performances. Les résultats ont servi à établir les liens entre les performances constatées et les caractéristiques particulières de chaque brise-glace.</p> <p>Des modèles de prévision des performances ont également été élaborés à partir de l'analyse des données en vraie grandeur: progression en champ de glace uniforme, franchissement de crêtes de pression, giration dans les glaces et navigation en eau libre.</p> <p>Les résultats des interviews, des analyses et de la modélisation ont été combinés pour offrir aux architectes navals et armateurs une information pratique sur les possibilités de combiner, à l'étape du projet, différentes caractéristiques particulières pour répondre aux impératifs d'un profil de mission donnée.</p> |                                                                  |                                  |                                                                                                      |                                                                    |  |
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## SUMMARY

This project addressed the influence of icebreaker design upon operational performance for the design parameters and features incorporated in the Canadian Beaufort Sea contemporary icebreakers and the German vessel Max Waldeck.

The Beaufort Sea vessels were developed in support of oil and gas exploration and development in the Canadian Beaufort Sea. Their mission roles are fundamentally ice defence, deployment and supply of offshore drillships and structures. Many innovative icebreaker design features and performance-enhancing systems were introduced in order to maximize the efficiency of these vessels in their operations.

The Max Waldeck, incorporating the innovative technology of the Waas bow, adds to the range of evolutionary designs.

Most of the vessels have been tested extensively in ice but, until recently, most of the data have been considered proprietary by the owners. Inevitably, there has been much speculation as to the relative performance of the vessels and the influence upon performance of specific features.

For this project the vessels' owners provided access to all test data.

The performance of the vessels was assessed in two ways:

- the qualitative approach of interviewing the operators
- the quantitative approach of analyzing full scale performance data

Data analysis is accurate but limited to a few idealized performance categories. The interview approach provides much more information but of a qualitative and potentially subjective nature. However, by ground-truthing one with the other, a reliable picture of overall performance was obtained.

Full-scale data were reduced to a common data base taking into account differences in environmental conditions, test procedures and vessel dimensions. Comparisons then allowed the influence of several parameters and features to be established.

Mathematical models in the form of empirical formulas for predicting the performance of vessels with different combinations of design features and hull parameters were then developed.

Ship performance trends arrived at from the interview



process were fully supported by the data analysis and modeling procedures. Furthermore, the responses of the ship masters provided much additional information on the relative performance of the vessels in a wide range of operational situations not covered by full-scale trials data. In many cases further assessments (of influence of design upon performance) of a qualitative nature but still of practical importance were achieved.

The outcome of the process is that the influence upon performance of several design parameters and features incorporated in this set of icebreaking vessels has indeed been established. Many are assessed quantitatively but some only qualitatively. For example, it has been shown how level ice resistance is affected significantly by buttock and flare angles at the bow and how reamers can enhance turning ability with no discernible operational penalty in ridge and open water performance. The high effectiveness of water lubrication on the ice in reducing level ice resistance has been shown in comparison with other lubrication systems. It is also shown and concluded from the data and operator interview that nozzles can be very efficient in ahead operations but cause major degradation of performance in the astern mode.

It is concluded that the project has provided a unique set of benchmark data for the performance of icebreakers in clearly specified conditions. The mathematical models produced predict performance for any combination of parameters within the same family of design parameters as in these ships. The influence of several design features and parameters upon performance is clearly identified together with information on the possible compromises which would be experienced by use of these features.

Practical data and information of this nature providing a wide range of actual operational and full-scale test data are invaluable to a designer and operator.

The approach used in this project proved effective in assessing extensively full-scale ship performance. Extending this approach to include other icebreakers would extend the range of design features and parameters for such an assessment. This would give the designer and operator a comprehensive database for design comparison purposes and a powerful tool for new designs.

## SOMMAIRE

Cette étude, qui visait à déterminer le lien entre les caractéristiques conceptuelles d'un brise-glace et ses performances, s'est concentrée sur les paramètres de conception et particularités des brise-glace actuels de la mer de Beaufort et du navire allemand MAX WALDECK.

Les navires de type Beaufort ont été développés pour assurer le soutien logistique des activités d'exploration et de mise en valeur des ressources pétrolières et gazières canadiennes de la mer de Beaufort. Ils ont essentiellement pour rôle d'escorter/remorquer à pied-d'oeuvre les bateaux et plates-formes de forage en haute mer et d'en assurer la protection contre les glaces. Pour maximiser leur efficacité, ils ont été dotés de nombreuses particularités innovantes pour la rupture des glaces et le relèvement des performances.

Le MAX WALDECK, équipé de la nouvelle proue Waas de technologie avancée, vient s'ajouter à la gamme des navires de conception innovatrice.

La plupart de ces navires ont fait l'objet d'essais poussés dans les glaces mais, jusqu'à tout récemment, les armateurs refusaient d'en divulguer les résultats, mis à part certaines données très fragmentaires. Dans ces conditions, il ne faut pas se surprendre des nombreuses spéculations concernant les performances relatives de ces navires et sur l'influence que peuvent avoir sur celles-ci diverses caractéristiques particulières.

Pour les fins de la présente étude, le contractant a obtenu l'autorisation de consulter la totalité des résultats d'essai.

Le contractant a suivi deux voies différentes pour évaluer les performances des navires:

- interview des capitaines et armateurs (approche qualitative)
- analyse des données de performances en vraie grandeur (approche quantitative).

L'analyse des données débouche sur des résultats précis, mais elle se limite à quelques catégories idéalisées de paramètres de performance. L'autre voie, celle des interviews, produit une information beaucoup plus abondante qui est cependant de nature qualitative et potentiellement subjective. Toutefois, en faisant les rapprochements appropriés entre les deux, on obtient une idée fiable des performances globales.

Les données des essais en vraie grandeur ont été ramenées à une échelle commune en prenant en compte les différences dans les conditions environnementales, entre les modes opératoires des essais et les dimensions des navires. De cette façon, les comparaisons permettent de déterminer l'influence de plusieurs paramètres et caractéristiques de conception.



Puis des modèles mathématiques de type empirique ont été élaborés pour prédire les performances selon différentes combinaisons de caractéristiques conceptuelles et de paramètres de forme de coque.

Les profils de performance qui se dégagent des interviews des capitaines et armateurs ont été entièrement confirmés par l'analyse des données et la modélisation mathématique. Par ailleurs, les interviews ont fourni beaucoup de renseignements additionnels sur les performances relatives des navires dans une gamme étendue de situations opérationnelles que les données des essais en vraie grandeur ne permettaient pas d'appréhender. Ainsi, on a pu mettre en évidence de nombreux autres liens entre paramètres de conception et performances, dont la connaissance est éminemment utile même si elle n'a pas encore été validée par des données chiffrées.

A l'issue de l'étude, on peut affirmer que la relation entre les performances et plusieurs paramètres de conception et caractéristiques a bel et bien été établie. Dans de nombreux cas, les constatations s'appuient sur des données chiffrées mais il en est d'autres où il s'agit d'une évaluation purement qualitative. Par exemple, il a été montré que la résistance à l'avancement dans les glaces est fortement tributaire des angles de dévers et des sections longitudinales de l'étrave et qu'un renflement latéral peut renforcer les aptitudes de giration dans les glaces sans répercussions négatives appréciables sur les performances en eau libre et lors de la charge des crêtes de pression. La grande efficacité de la lubrification de l'interface glace-étrave par jets d'eau basse pression par rapport à d'autres modes de lubrification a été établi en ce qui concerne la réduction de la résistance à la marche dans des glaces uniformes. L'analyse des données et des interviews permet d'affirmer que les tuyères de protection des hélices peuvent être très efficaces en marche avant, au prix cependant d'une sérieuse dégradation des performances en marche arrière.

Les chercheurs considèrent que l'étude a permis de dégager un jeu unique de données repères sur les performances des brise-glace dans des conditions clairement définies. Les modèles mathématiques élaborés permettent de prévoir les performances pour n'importe quelle combinaison de paramètres à l'intérieur de la famille de paramètres de conception représentée par ces navires. L'influence de plusieurs caractéristiques et paramètres de conception sur les performances a été clairement définie et les concepteurs peuvent dorénavant compter sur une information utile concernant les compromis que suppose le choix de telle ou telle caractéristique.

Il faut dire que ce type de données et d'informations pratiques, fondé sur une gamme étendue de conditions d'exploitation et d'essais en vraie grandeur, constitue une aide inestimable pour les projeteurs et exploitants de brise-glace.

L'approche retenue par le contractant s'est avérée un moyen efficace d'évaluer de façon exhaustive les performances réelles d'un brise-glace. En appliquant cette méthode à d'autres brise-glace, on pourrait étendre la gamme des caractéristiques et paramètres de conception pouvant être pris en compte pour une telle évaluation. Cela fournirait aux concepteurs et armateurs une base de données exhaustive sur laquelle fonder les choix techniques en plus de constituer un outil performant pour l'étude de nouveaux brise-glace.

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## **1.0 INTRODUCTION**

### **1.1 Background**

Seven major icebreakers were developed in support of oil and gas exploration and development in the Canadian Beaufort Sea during the late seventies and early eighties. They depart in design considerably from any other icebreaker or group of icebreakers. They incorporate a range of innovative icebreaking features and performance-enhancing systems that have not been used before. Amongst them they have many variants. The ships have been relatively inexpensive to build and operate and have performed well in service. In many respects they have exceeded the original performance expectations. In other respects there have been performance compromises as a consequence of the special roles of these ships as well as the new technology applied. Most of the ships have been extensively tested in ice. Yet, until recently, most of the data have been considered proprietary by the owners. This has prevented a thorough analysis of their individual and collective merits and deficiencies.

Another ship incorporating innovative technology is the Max Waldeck. The Waas bow on this German ship adds to the range of evolutionary designs.

There has been much speculation and occasional comparisons of various aspects of the performance of the Beaufort Sea icebreakers and the Max Waldeck. For this project, the owners of the ships and the data, namely Canadian Marine Drilling Ltd. (CANMAR), BeauDril Limited and Arctic Transportation Limited (ATL) have allowed this unique opportunity to gain access to all of the performance data on their icebreakers and to interview their operators. The available data on the Max Waldeck is used to correlate its performance with the Beaufort Sea Icebreakers.

This project is an extensive evaluation of the Beaufort Sea icebreaker technology, enhanced with the Max Waldeck data. It is targeted at the operators and designers of icebreakers. Icegoing performance in a wide range of performance categories is analysed and evaluated and the influence of design features on performance is determined.

### **1.2 Project Overview**

The roles for the Beaufort Sea Icebreakers vary from ship to ship but generally they have been established by the ship owners and operators as follows, in order of priority:

- Ice defence
- Anchor Handling
- Supply
- Towing
- Escort

These operational roles support drilling operations in an environment with all types and thicknesses of first year ice as well as frequent occurrences of multi-year ice. All this is in an area with a short open water season and with limited wave exposure. This departs from the traditional missions and operating environments of other icebreakers.

An icebreaker's mission profile incorporates several roles each of which involves different aspects of a vessel's performance. In turn, each performance component can best be achieved through incorporation of specific design features. (See Figure 1.1). The designer's role is that of selecting that set of design features which satisfies the mission profile in the optimal fashion. This process often involves compromises.

In order to make the decisions necessary for the optimum design, it is evident that the influence of design features upon performance and of performance categories upon the ability to perform the mission roles must be understood.

This is the essence of the project objectives.

To achieve this, the project has three components:

1. Operator interview of the practical performance of their ships in executing the mission roles.
2. Analysis of full scale performance data and evaluation of the influence of design parameters upon performance.
3. Analytical models to calculate various aspects of the performance.

The performance categories analyzed in this project are:

- level ice performance
- channel performance
- ridge performance
- manoeuvring performance
- open water performance
- transit performance
- propulsion performance

The design features are in three categories:

- Hull form
- Auxiliary devices
- Propulsion configuration

The outline of the study by chapter is given below:

Chapter 2 : Background information of the ships, the tests and the environment

Chapter 3 : Analysis and results of operator interview.

Chapter 4 : Level ice performance analysis

Chapter 5 : Channel performance analysis

Chapter 6 : Manoeuvrability analysis

Chapter 7 : Open water performance analysis

Chapter 8 : Ridge performance analysis

Chapter 9 : Transit performance analysis

Chapter 10: Propeller performance in ice analysis

Chapter 11: Development of performance estimation models

Chapter 12: Conclusions

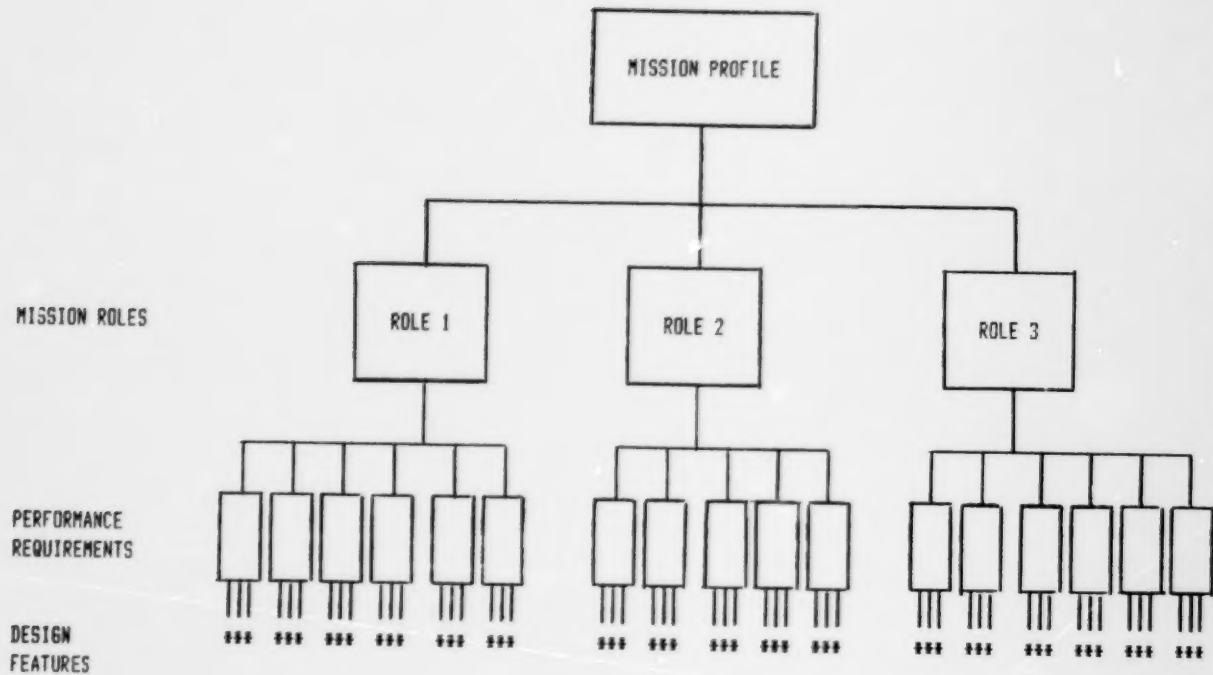
Chapter 13: Recommendations

Background information for the data in the above chapters is contained in the appendices. The owners of the data have requested that the original full scale test data and the lines plans of the ships remain confidential. This is therefore contained in restricted circulation documents (Appendices D and E).



FIGURE 1.1

MISSION PROFILE AND DESIGN FEATURES



## 2 BACKGROUND INFORMATION

### 2.1 Ships

This study involves the following eight ships:

Kigoriak - Canadian Marine Drilling  
Robert Lemeur - Canadian Marine Drilling  
Terry Fox and Kalvik - BeauDril  
Ikaluk and Miscaroo - BeauDril  
Arctic Ivik - Arctic Transportation Limited  
Max Waldeck - West German Ministry of Transport

The first seven ships were designed to support drilling operations in the Beaufort Sea. The BeauDril ships are two pairs of sister ships. The Max Waldeck is a harbor icebreaker that was converted by fitting a Waas bow to assess the advantages of this bow form. Figures 2.1, 2.2, and 2.3 show the general arrangements of each of these ships. Table 2.1 gives relevant details of the ship particulars.

The hull forms for these vessels are considered confidential by the owners. They are given in a restricted circulation document as Appendix E.

To understand the design and operation of each of the ships a brief description of the design mission role and the key design features is given below. All of the Beaufort Sea vessels have flat plate and single curvature plate hulls, incorporating chines, to minimize construction costs. Further details are found in Appendix B.

#### **Kigoriak**

The Kigoriak was designed as an ASPPR class 3 ship to extend the Canmar drilling season based on the lessons learned from the operation of four class 2 ships. She was designed to perform the following missions:

- Ice defence
- Research
- Anchor handling
- Supply

To increase operational efficiency and reduce the cost the ship incorporated many innovative design features not found on previous icebreakers. They included:

- Spoon shaped bow
- Reamers
- Short bow ending in a chine to minimize shoulder ice crushing

Parallel midbody  
Water wash to pump water onto the ice ahead of the  
bow/ice contact  
Single centreline controllable pitch propeller in a  
nozzle

#### **Robert Lemeur**

The Robert Lemeur was designed as a class 3 ship to perform the following mission roles with particular emphasis in the design on shallow draft operation with maximum deadweight for supply operations and improvements in performance over the Kigoriak:

Early and late season supply  
Icebreaking/ice defence  
Research (A model for the Arctic Pilot Project LNG carrier)

The major differences between the Robert Lemeur and the Kigoriak are:

A high block coefficient for maximum deadweight  
Twin CP propellers in nozzles  
Ice island aft to reduce propeller/ice interaction  
Reduced bow angles to reduce the resistance

#### **Terry Fox and Kalvik**

These sisterships were designed as an integral part of Gulf Canada Resources second generation Beaufort Sea drilling system for extended season exploratory drilling. They are designed for heavy icebreaking. The design mission roles for these class 4 ships are:

Ice management  
Long distance towing  
Anchor handling  
Vessel escort  
Supply

The bow shape is designed for low resistance in ice and a wedge was fitted under the forebody to reduce the amount of ice entering the propellers and to maintain a clear channel. Twin open controllable pitch propellers were fitted to ensure that thrust can be maintained in all ice conditions. A single rudder is fitted.

#### **Ikaluk and Miscaroo**

These class 4 sisterships have a somewhat complementary role to the Terry Fox/Kalvik role as they are required to be highly manoeuvrable in open water and light ice for running

anchors and supply duties in tight quarters. The mission roles include:

- Anchor handling
- Supply
- Ice management
- Towing
- Ice escort

The ships contain many of the same design features as the other sisters. The major difference is that the twin controllable pitch propellers are located in nozzles to maximize the thrust and reduce the required power. Twin rudders are fitted for manoeuvrability.

#### **Arctic Ivik**

The Arctic Ivik is a class 2 ship designed to support Beaufort Sea drilling operations. The design mission roles were:

- Supply with high deadweight on a shallow draft
- Anchor handling
- Survey requiring good station keeping
- Ice management

The bow is designed for low resistance and incorporates chines for reduced construction costs. The hull form aft is designed to protect the twin controllable pitch propellers from ice interaction.

#### **Max Waldeck**

The Max Waldeck was fitted with a Waas bow to test this bow form in full scale. The bow is claimed to break the ice initially in shear and then by bending fracture. The hull is designed to displace the broken ice to the sides leaving a clear channel. Because of the size of the existing ship the bow length is shorter than required for the optimal Waas form. In addition the transition between the new bow and the existing hull form is a compromise. The ship was fitted with a Jastram air/water jet system to reduce friction and enhance the ice clearing. The single propeller was fitted with a nozzle to augment the thrust.

Coefficients for the bows of each of the vessels are given in table 2.2.

#### **2.2 Trials**

The trials performed on the ships in ice are given in Table 2.3. With the exception of the Arctic Ivik trials, all

of the trials were dedicated solely to testing the ships. The data for the Arctic Ivik were obtained on a supply voyage from Tuktoyaktuk to an Esso drilling site. The sources of the data for the trials are also given in the table.

As can be seen from the table all of the trials, with the exception of November, December 1982 trials of the Kigoriak and the Robert Lemeur and the January 1984 trials of the Terry Fox and the Ikaluk were conducted at different times of the year. The trials were also conducted in different locations. The Max Waldeck trials were carried out in the Baltic Sea. The trials on the other ships were carried out in the southern Beaufort Sea. The sole exception to this was the trials on the Kalvik which were conducted in Viscount Melville Sound. Because of the different locations and dates for the trials the ice conditions would be expected to differ. On ice measurements were made to determine the ice properties. These are discussed in sub-section 2.3.

Another factor required in order to analyse the data is the condition of the hull during the trials, as it will determine the hull/ice friction factor. This information was not well recorded for the trials. From discussions with the operators and knowledge of the drydocking history of the ships it was possible to determine the most likely condition of the hull coating during the trials.

The Kigoriak was delivered to the operator without Inerta coating. During the first season of operation the bare steel hull remained smooth with little degradation. By the time trials were conducted in May 1982, the hull had become severely corroded with deep pitting. As the performance of the Kigoriak was also severely degraded the hull was blasted and coated with Inerta prior to the trials in the winter of 1982.

The Robert Lemeur was delivered with an Inerta coating in the fall of 1982. At the first drydocking in November 1983, the Inerta in the bow region had almost disappeared due to a faulty application procedure. For the winter 1982 tests, the most likely hull condition was intact Inerta with little bare steel as the ship had seen little ice operation. By June 1983, with a whole season of operation, the hull most likely had large areas without Inerta, although the steel would still have been smooth.

All the other ships had Inerta coatings in good condition.

Open water trials were performed on each of the ships during the builder's trials. Some limited open water testing was performed on some of the ships to confirm speed versus power, establish the bollard thrust, and determine the open water turning circles. No seakeeping tests were performed.



## 2.3 Environmental Data

### 2.3.1 Introduction

All of the ships in this study have been tested in different locations, at different times of the year and in different years. In order to make valid comparisons of the performance data, the environmental conditions should be analysed to determine the similarities and differences and, where feasible, make corrections to the performance data to bring the data to a common base.

It is well known from model tests and full scale trials that ice thickness, ice strength, and friction all have a major impact on the performance. In addition other environmental factors such as wind speed and direction relative to the vessel's direction and temperature have an influence on the performance.

Ideally trials should be conducted in known and measured environmental conditions using accepted and defined procedures. In addition to assess the overall operational capabilities of the ship, it should be tested in as wide a range of environmental conditions as possible.

For the ships in this study, trials have been conducted in level ice, ridges, broken channels and in transit which involves the preceding categories plus open water. The environmental conditions for each category that are necessary for quantification of the trial conditions are as follows:

- Level ice - ice strength  
ice thickness  
snow cover  
general conditions, eg presence of melt water
- Ridges - thickness profile including sail height and bottom  
thickness of consolidated layer  
snow cover distribution  
strength  
make-up of unconsolidated layer ie. thickness and size of pieces
- Channels - piece size and concentration  
degree of refreezing, or age  
channel width

A summary of the environmental data collected during the trials is contained in Appendix A. The following sections contain a discussion of the major issues concerning interpretation of the environmental data.



### 2.3.2 Ice Strength

The dependency of ice resistance on ice strength has been established from model tests conducted in ice model basins since the late 1960's. To the project team's knowledge no such analysis has been performed in generally available full scale trials due to the lack of full scale data in different ice strengths with all other parameters remaining constant. The major grouping of ice strength for the trials conducted in the Beaufort Sea has been winter and spring/fall testing. The spring/fall ice is much weaker than the winter ice. Hand in hand with the reduction of strength come other changes in properties due to the increased ice temperatures and changes in the snow cover. The friction between the hull and ice/snow is modified and the fracture behaviour of the ice changes as the warmer ice is less brittle. It is clear that the differences in ice properties can have a major effect on resistance and performance. Based on present knowledge, it is not clear how to modify the performance data to account for differences in ice strengths when other properties are also changing.

For this reason it was decided to segregate the ship performance data into the two groups; winter and spring/fall testing. Traditionally, only the bending strength has been used as an index of the strength when discussing the ice resistance. This is appropriate as an index providing other properties such as friction remain similar.

All the Beaufort Sea winter trials have been conducted in air temperatures below -20 degrees C and with a snow cover up to 20 cm present. This is judged to give similar friction factors for hulls coated with similar materials.

The environmental data contains information that could be used to assess the strength in many different ways; temperature and salinity profiles, crystallography, bore hole jack measurements, cantilever beam and uniaxial strength. The common denominator for all the data is the temperature/salinity profile. The other measures are not present in all the data sets, nor is there sufficient information to ensure that all the testing was conducted to the same standards.

Based on discussions with IMD, the following methodology was used to calculate a flexural index strength from the temperature/salinity profiles:

- 1) Use the formula below to calculate the brine volume at each level from the temperature/salinity readings;

$$V_b = S/1000(0.532 - 49.185/T)$$

where  $V_b$  = brine volume  
S = salinity (ppt)  
T = temperature ( $^{\circ}\text{C}$ )

2) Take the average of the brine readings over the full depth. 3) Using the average brine volume calculated in 2) calculate the flexural strength index from the following formula;

$$f = 850(1 - 0.72 \cdot V_b^{0.5})$$

where  $f$  = flexural strength index (KPa)

Winter data exists for the Kigoriak, Terry Fox, Ikaluk, and the Robert Lemeur. The analysis of the data is presented in Appendix B. The results are tabulated below;

| SHIP             | YEAR<br>TESTED | AVER.FLEX<br>INDEX | RANGE      |
|------------------|----------------|--------------------|------------|
| Kigoriak         | 1980           | 492 kPa            | 436 to 550 |
|                  | 1982           | 458 kPa            | 444 to 468 |
| Terry Fox/Ikaluk | 1984           | 585 kPa            | 487 to 655 |
| Robert Lemeur    | 1982           | 458 kPa            | 444 to 468 |

The Arctic Ivik was tested in early November 1985 in temperatures similar to the Robert Lemeur and hence the strength was judged to be similar ie. 458 kPa.

These strengths are indicative of winter conditions and reflect the different test areas and times of testing. The overlap of strengths suggests that the conditions can be considered as similar.

The Max Waldeck was tested in the Baltic in the winters of 1981 and 1982. The reported strengths are as follows;

|      |               |
|------|---------------|
| 1981 | 450 - 500 kPa |
| 1982 | 300 - 340 kPa |

Assuming that these data are similar to the others (ie. they have been calculated in a similar manner), then the Max Waldeck 1982 is close to the spring/fall data, whereas the 1981 data is close to the winter data for the Beaufort Sea ships.

Summer data exists for the Kigoriak and the Kalvik. The flexural strength index is tabulated below and calculated in Appendix B;

|          |               |                      |
|----------|---------------|----------------------|
| Kigoriak | 1980 - spring | 150 kPa              |
| Kalvik   | 1986 - fall   | 233 kPa (150 to 400) |

In addition to the temperature/ salinity data, there is limited data available on the compressive strength as evaluated by borehole jack measurements. As for the flexural

strength indices the following values should be treated as indices of the compressive strength, rather than absolute measures of the strength;

|                           |                  |
|---------------------------|------------------|
| Kigoriak - winter         | 18.0 to 26.0 MPa |
| Terry Fox/Ikaluk - winter | 23.0 to 26.0 MPa |
| Kigoriak - spring         | 10.2 to 10.5 MPa |
| Kalvik - fall             | 4.5 to 10.7 MPa  |

This data clearly shows that there is a major difference between winter and summer strengths, and provides further confirmation of the need to treat the summer and winter test data separately.

### 2.3.3 Level Ice

In addition to the strength, the parameters to define the characteristics of the level ice are the snow cover, the thickness and the general conditions.

Snow cover was present in all the tests and its thickness was measured. As described in the data analysis section, half the snow thickness was added to the ice thickness to give an equivalent ice thickness. This is in accordance with the recommendations of ITTC 87.

In the Beaufort Sea tests, sufficient holes were drilled along the test path to determine the thickness and establish the uniformity of thickness. In the Kalvik tests in the fall of 1986, the ice thickness was irregular due to a hummocky surface profile and the presence of extensive melt pools. The holes drilled during these tests established the non-uniformity of the ice and snow thicknesses.

The spring/fall tests are characterised by non-uniform surface conditions, with the snow cover irregular in thickness and the presence of melt pools, either liquid or refrozen. These conditions give rise to much lower coefficients of friction than the winter conditions where cold, dry snow is present.

### 2.3.4 Ridges

The penetration tests conducted with the Kigoriak and the Robert Lemeur were in the winter, in ridges formed from first year ice. Sufficient holes were drilled along the length of the route to establish the thickness distribution of both ice and snow and the degree of consolidation. As shown in the following table the major differences between the two sets of ridges was the thickness and the degree of consolidation. This is due to the time of testing for each ship. The Kigoriak was

tested later in the season when the ridges were more mature and hence had achieved a greater degree of consolidation and thickness.

|                              | Jan. - Mar.<br>1980 | Nov. - Dec.<br>1982 |
|------------------------------|---------------------|---------------------|
| Mean average thickness       | 8.25 m              | 6.53 m              |
| Mean length                  | 140 m               | 100 m               |
| Mean maximum keel depth      | 16 m                | 12 m                |
| Mean maximum sail height     | 2.40 m              | 2.00 m              |
| Mean consolidation thickness | 1.60 m              | 1.20 m              |

The compressive strength index within the consolidated layer as measured by borehole jack ranged from 10.0 to 24.8 MPa.

The penetration tests conducted with the Kalvik were in the fall in thick first year and old ice, much of which was in a deteriorated condition with melt pools present. The compressive strength index was an average of 4.9 MPa for the first year ice and 13.8 MPa for the old ice. These have been classified as spring/fall ramming tests as opposed to the winter tests of the Kigoriak and the Robert Lemeur.

### 2.3.5 Channels

The trials in channels were conducted in the track made by the ship when carrying out the ahead level trials. Piece size and concentration were not noted, but would be expected to vary according to the speed of the ahead trial and the ice clearing capability of the ship. The degree of refreezing was not noted, however the channel trials were in general conducted immediately after the ahead trials and the refreezing would be insignificant.

### 2.3.6 Transit

The transit data for the Kigoriak was primarily obtained from a trip in January 1980 from Summers Harbour to McKinley Bay, covering a distance of 291 km. The average level ice thickness was 0.90 m and 1710 significant ridges (ie heights greater than 0.3 m) were encountered. Heights of sails of all the ridges were observed and the depth of consolidation was estimated to be 1.6 m.

Transit data for the Kigoriak during the spring breakout in mid-June 1980 was also documented in an average ice thickness of 1.75 m.

The transit data for the Terry Fox was tested conducted in January 1984 in five separate time periods covering a total

distance of 16.8 km. The average level ice thickness was 0.80 m and a total of 224 ridges were encountered. Heights of all the ridges were observed, however the degree of consolidation was not measured.

Because of the different observation techniques the two data sets are not directly comparable.

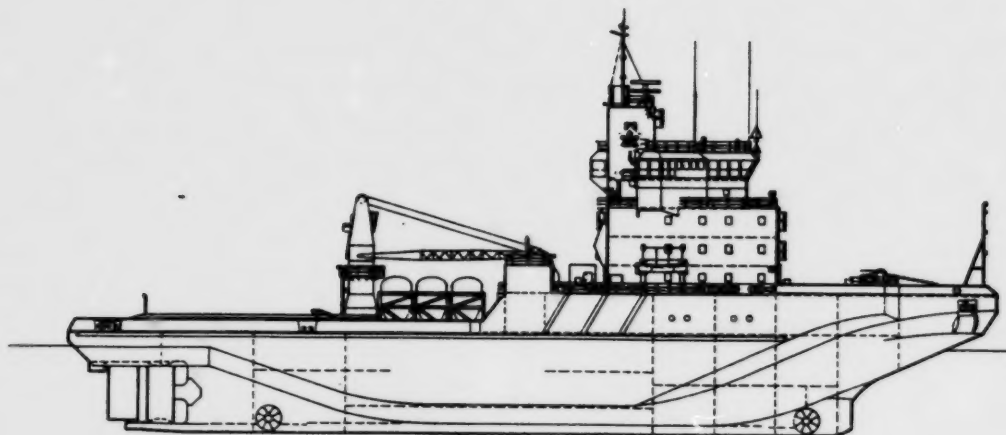
#### 2.3.7 Wind

The majority of the tests were conducted in low wind speed conditions. Some of the Ikaluk tests were conducted with wind speeds from 25 to 50 knots from astern. An investigation of the affected points in Appendix A, showed that the power could be underestimated for low power, low speed data points by as much as 34%. Removal of the affected points had little effect on the original curves of power versus speed.

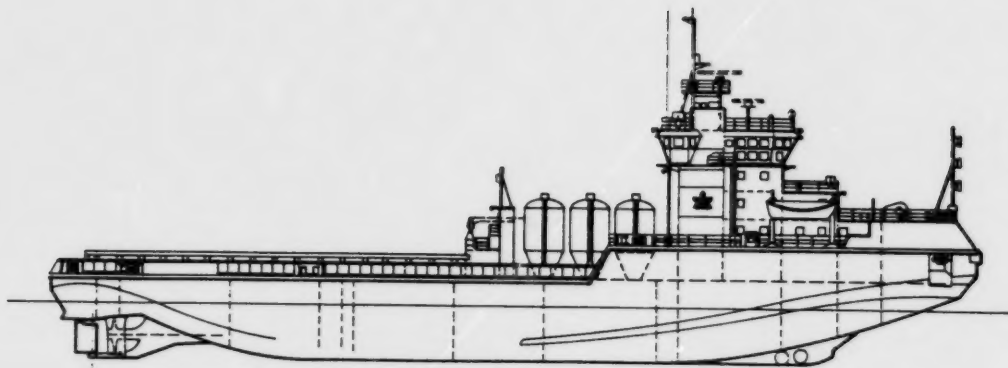
Trials should be conducted in conditions with low wind speeds as it is difficult to account for all the possible effects of the wind. In addition to the increase or decrease of resistance (depending on the wind direction), the wind may also pressure the ice increasing the ship resistance to an unquantifiable degree.



FIGURE 2.1  
GENERAL ARRANGEMENT  
Kigoriak and Robert Lemeur



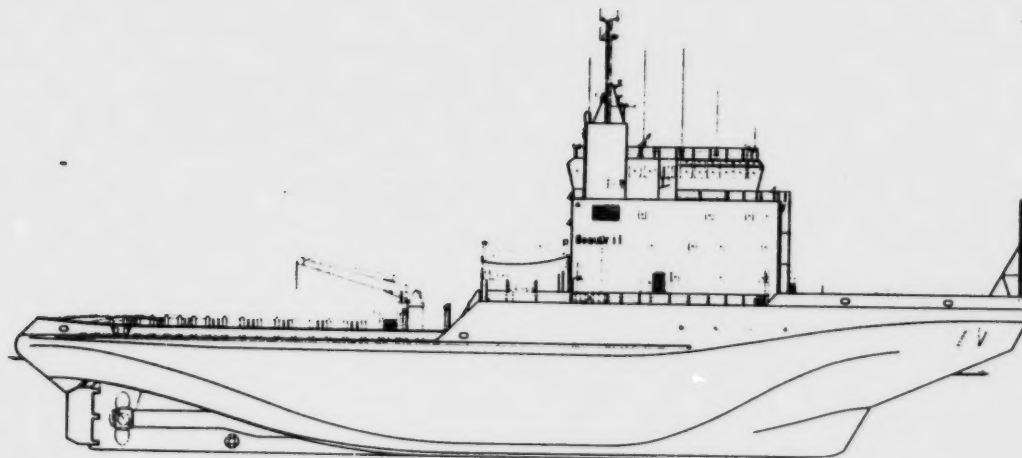
2.1.a) Kigoriak



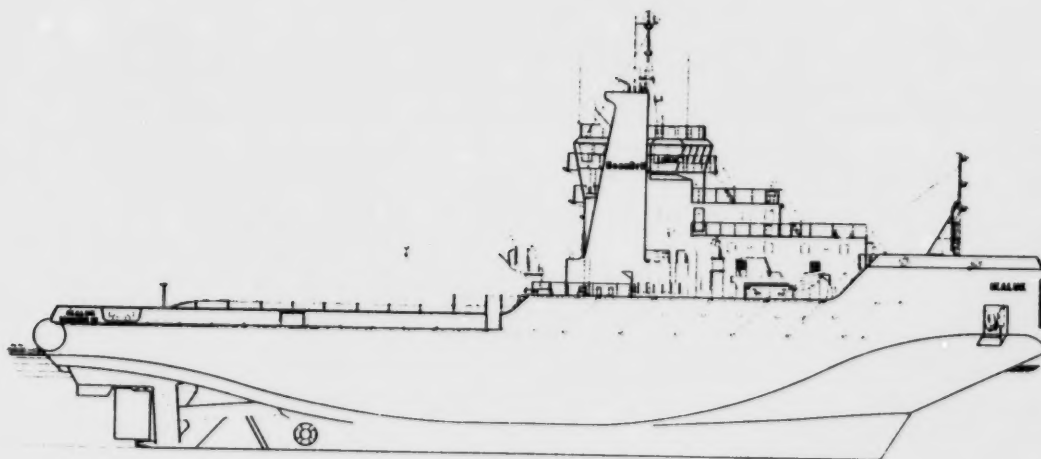
2.1.b) Robert Lemeur



FIGURE 2.2  
GENERAL ARRANGEMENT  
Terry Fox and Ikaluk

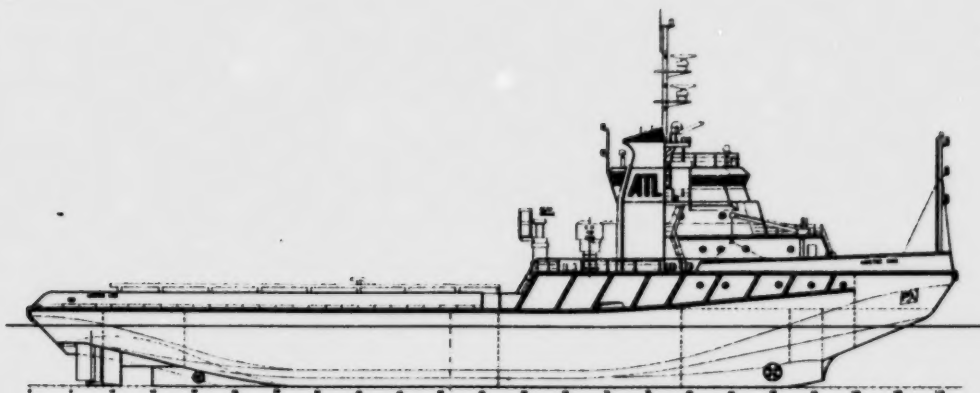


2.2.a) Terry Fox

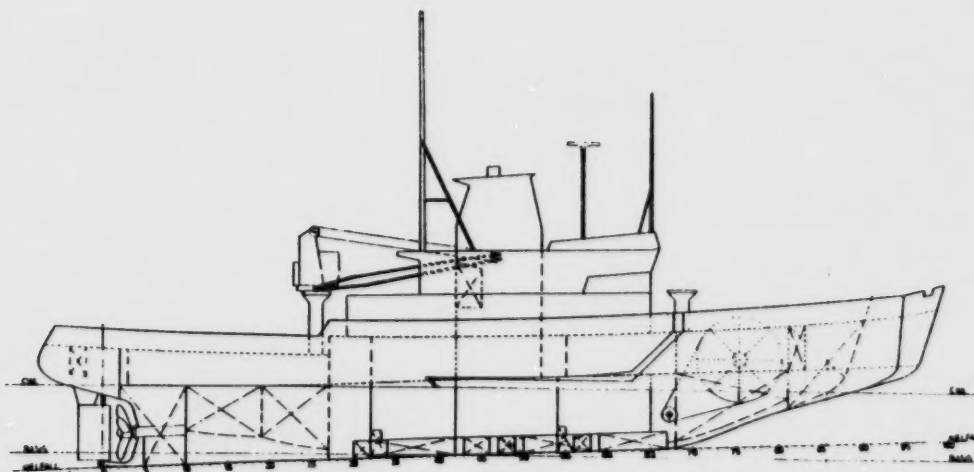


2.2.b) Ikaluk

FIGURE 2.3  
GENERAL ARRANGEMENT  
Arctic Ivik and Max Waldeck



2.3.a) Arctic Ivik



2.3.b) Max Waldeck

TABLE 2.1

## SHIP PARTICULARS

|                        | KIGORIAK             | ROBERT LEMEUR        | TERRY FOX          | IKALUK               |
|------------------------|----------------------|----------------------|--------------------|----------------------|
| ASPPR CLASS            | 4                    | 3                    | 4                  | 4                    |
| LOA M                  | 90.00                | 82.20                | 88.00              | 78.85                |
| LBP M                  | 79.34                | 78.00                | 75.00              | 70.00                |
| LWL M                  | 84.20                | 79.13                | 81.40              | 76.20                |
| B M                    | 19.25 (OVER REAMERS) | 19.03 (OVER REAMERS) | 17.45 AT WATERLINE | 16.61 AT WATERLINE   |
| D M                    | 10.00                | 7.5                  | 10.0               | 9.70                 |
| T M                    | 8.50                 | 5.5                  | 8.0                | 7.50                 |
| DISPLACEMENT TONNES    | 6616                 | 5538                 | 6824               | 5047                 |
| CB                     | 0.55                 | 0.70                 | 0.63               | 0.53                 |
| LIGHTSHIP TONNES       | 4927                 | 3163                 | 4991               | 3952                 |
| DWT TONNES             | 1691                 | 2690 MAX AT 5.67 M   | 1708               | 1940                 |
| FUEL TONNES            | 1146                 | 1850                 | 1650               | 1482                 |
| REAMER WIDTH M         | 1.0 / SIDE           | 0.5 / SIDE           | -                  | -                    |
| LENGTH //MIDBODY M     | 56                   | 50                   | 26                 | 47                   |
| SHAFT POWER MW         | 12.2                 | 7.06                 | 17.3               | 11.12                |
| MACHINERY TYPE         | 2 MED SPD GEARED     | 2 MED SPD GEARED     | 4 MED SPD GEARED   | 4 MED SPD GEARED     |
| PROPELLERS NUMBER      | 1                    | 2                    | 2                  | 2                    |
| DIAMETER M             | 5.3                  | 3.0                  | 4.8                |                      |
| TYPE                   | CPP                  | CPP                  | CPP                | CPP                  |
| PITCH AH/AS DEG        |                      | 29.3/22              |                    |                      |
| TIME AH/AS S           | 25                   | 5                    |                    |                      |
| NOZZLES                | YES                  | YES                  | NO                 | YES                  |
| BOLLARD PULL TONNES    | 182.3                | 116.8                | 181.1              | 173.3                |
| RUDDERS NUMBER         | 1                    | 2                    | 1                  | 2                    |
| MAX ANGLE DEG          | 40                   | 45                   | 37                 | 37                   |
| AREA M**2              | 14.00                | 9.74                 | 13.0               |                      |
| HO/HO TIME S           | 14.50                | 12                   | 12.6               |                      |
| BOW THRUSTER NUMBER    | 1                    | 2                    | 1                  | 1                    |
| TYPE                   | CPP 1200 BHP         | CPP 900 BHP EACH     | AIR BUBBLER        | OMNI THRUSTER 1200HP |
| STERN THRUSTER NUMBER  | 1                    |                      | 1                  | 1                    |
| TYPE                   | CPP 1200 BHP         |                      | CPP                | CPP 800 HP           |
| AUXILIARIES WATER WASH | 200 M**3/MIN         | 100 M**3/MIN         |                    |                      |
| HP WATER               |                      | 18.7 M**3/MIN        |                    |                      |
| BUBBLER                |                      | FWD 2X100 HP         | WARTSILA           |                      |
|                        |                      | AFT 1X100 HP         |                    |                      |
| AIR WATER              |                      |                      |                    | OMNI PHASOR 1200 HP  |
| RAPID HEELING          |                      | 160 TONNES IN 94 S   |                    |                      |
| TRIM SYSTEM            |                      |                      |                    |                      |

TABLE 2.1 CONTINUED

## SHIP PARTICULARS

|                        | ARCTIC IVIK       | MAX WALDECK          |
|------------------------|-------------------|----------------------|
| ASPPR CLASS            | 2                 | N/A                  |
| LOA M                  | 67.40             | 55.34                |
| LBP M                  | 60.75             |                      |
| LWL M                  | 64.70             | 46.58                |
| B M                    | 14.0              | 13.10                |
| D M                    | 5.8               |                      |
| T M                    | 4.27              | 4.0                  |
| DISPLACEMENT TONNES    | 2375              | 1295                 |
| CB                     | 0.62              | 0.52                 |
| LIGHTSHIP TONNES       | 1649              |                      |
| DWT TONNES             | 1508 MAX AT 4.9 M |                      |
| FUEL TONNES            | 826               |                      |
| REAMER WIDTH M         |                   | 0.77                 |
| LENGTH //MIDBODY M     | 51                | 31                   |
| POWER MW               | 5.37              | 2.31                 |
| ENGINE TYPE            | 2 MED SPD GEARED  | DIESEL ELECTRIC      |
| PROPELLERS NUMBER      | 2                 | 1                    |
| DIAMETER M             | 3.1               | 3.25                 |
| TYPE                   | CPP               | CPP                  |
| PITCH AH/AS DEG        |                   |                      |
| TIME AH/AS S           | 8 S               |                      |
| NOZZLES                | YES               | YES                  |
| BOLLARD PULL TONNES    | 88.9              | app. 30              |
| RUDDERS NUMBER         | 2                 | 1                    |
| MAX ANGLE DEG          |                   |                      |
| AREA M**2              | 8.18              | 5.9                  |
| HO/HO TIME S           | 12                |                      |
| BOW THRUSTER NUMBER    | 1                 | 0                    |
| TYPE                   | CPP 670 HP        |                      |
| STERN THRUSTER NUMBER  | 1                 | 0                    |
| TYPE                   | CPP 250 HP        |                      |
| AUXILIARIES WATER WASH |                   |                      |
| HP WATER               |                   | 5 IMPULSE JETS /SIDE |
| BUBBLER                |                   |                      |
| AIR WATER              |                   | JASTRAM AIR/WATER    |
| RAPID HEELING          |                   |                      |
| TRIM SYSTEM            |                   |                      |

TABLE 2.2

## BOW FORM COEFFICIENTS

(ALL VALUES IN DEGREES)

|                        | KIGORIAK | ROBERT LENEUR | TERRY FOX | IKALUK | ARCTIC IVIK | MAX WALDECK |
|------------------------|----------|---------------|-----------|--------|-------------|-------------|
| STERN ANGLE            | 24       | 20            | 24        | 25     | 22          | 16          |
| AVERAGE BUTTOCK ANGLE  | 24       | 20            | 23        | 25     | 24.5        | 16          |
| AVERAGE FLARE ANGLE    | 57       | 77.5          | 47        | 52     | 60          | 81.5        |
| AVERAGE ENTRANCE ANGLE | 34.4     | 58.7          | 25.5      | 30.8   | 38.3        | 88.7        |

TABLE 2.3

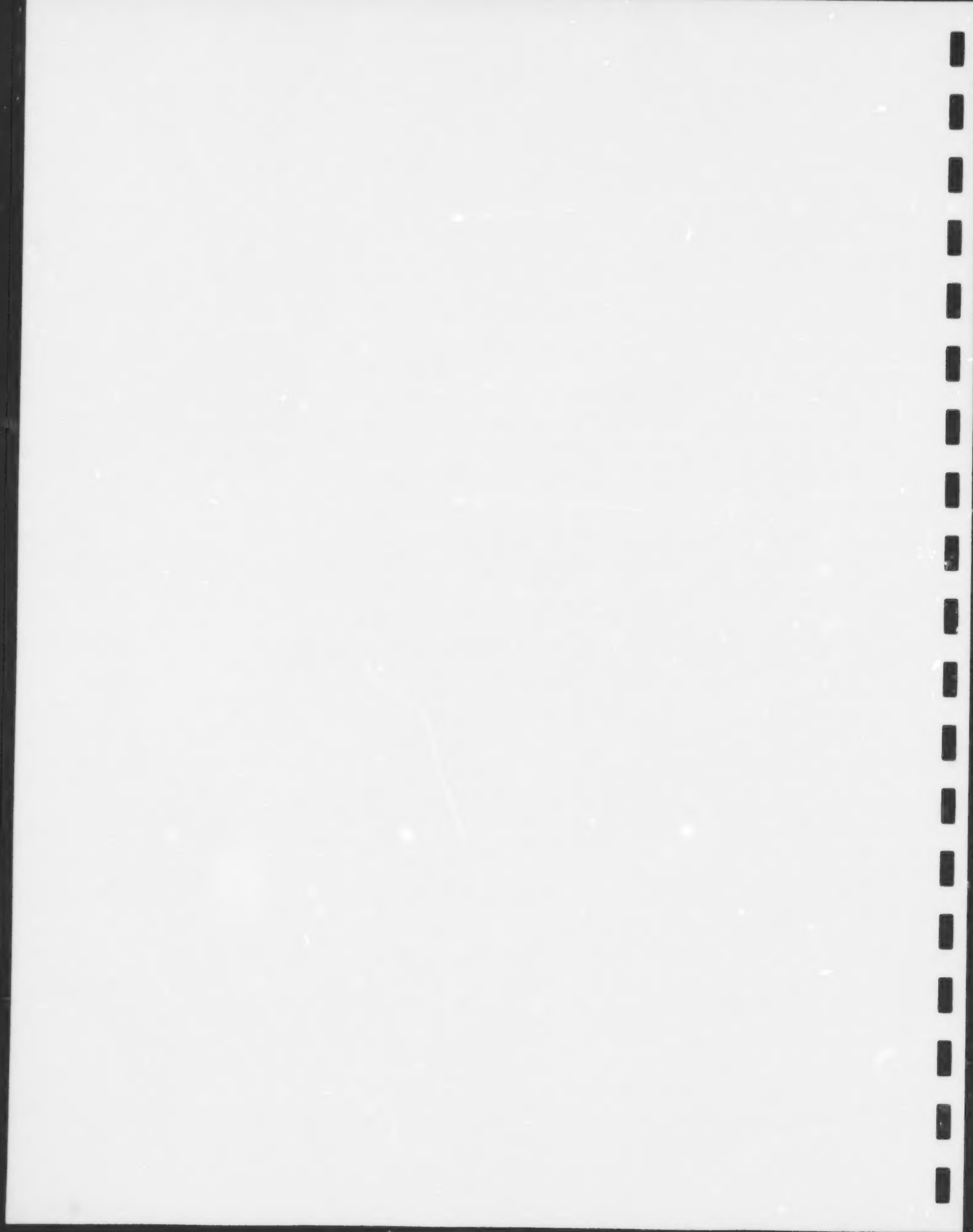
## TRIALS MATRIX

| SHIP          | DATE OF TRIALS                | TRIALS PERFORMED | HULL CONDITION           | TEST REFERENCES   |
|---------------|-------------------------------|------------------|--------------------------|-------------------|
| KIGORIAK      | WINTER 1979-80 (OCT. TO MAR.) | L,C,R,M,T,P      | SMOOTH BARE STEEL        | 1,3,4,6,8,9,10,11 |
|               | JUNE 1980                     | L,M              | SMOOTH BARE STEEL        | 18                |
|               | MAY 1981                      | L,R,M            | ROUGH BARE STEEL         | 12,18             |
|               | NOV., DEC. 1982               | L                | INERTA                   | 5,6,16,18         |
| ROBERT LEMEUR | NOV., DEC 1982                | L,C,R,M,P        | INERTA                   | 2,5,6,7,15,17,18  |
|               | JUNE 1983                     | L                | INERTA (SOME BARE STEEL) | 6,18              |
| TERRY FOX     | JAN. 1984                     | L,C,M,T          | INERTA                   | 19                |
| KALVIK        | AUG., SEPT 1986               | L,C,R,M,         | INERTA                   | 21                |
| IKALUK        | JAN. 1984                     | L,C,M            | INERTA                   | 20                |
| ARCTIC IVIK   | OCT., NOV. 1985               | L,C,M,T          | INERTA                   | 25                |
| MAX WALDECK   | MAR. 1981, MAR. 1982          | L,C,R,M          | INERTA                   | 27,28,29          |

## KEY

L - LEVEL ICE  
 C - CHANNEL  
 R - RIDGES  
 M - MANOEUVRING  
 T - TRANSIT  
 P - PROPULSION/ICE INTERACTION





### 3.0 ANALYSIS OF QUESTIONNAIRE

#### 3.1 Introduction

The purpose of the questionnaire was to obtain a qualitative evaluation of the effect of a vessel's design features on its performance in a much wider range of performance categories and mission roles than would normally be evaluated from dedicated trials.

Masters of each of the vessels used in the study have accumulated a wealth of experience on the performance of their vessels under a variety of operating conditions. The master's interpretation and evaluation of their vessel's performance greatly extends the knowledge about the complex interplay between the design features and the mix of performance categories encountered while performing assigned mission roles. When designing ships for a specific role, this knowledge is invaluable for choosing features which enhance performance and avoiding those features which detract from the performance.

It was anticipated that the information gathered might be somewhat biased. The questionnaire was therefore structured to minimize this effect. However, it was not possible to eliminate an operator's preference for a feature, which although making an operators job easier, may not be justified in terms of overall vessel economics. Typical examples of this would be excessive horsepower or nozzles.

Full details of the development of the questionnaire are given in Appendix A, which also contains a blank copy of the questionnaire.

The primary emphasis in the questionnaire was the operator's evaluation of the vessel's design features in the performance of the vessel.

The design features considered were:

- Bow and stern shapes
- Propeller arrangement
- Rudder location
- Reamers
- Length of parallel mid body
- Sloped midships sides
- Bow wedge
- Auxiliaries (friction reduction)
- Hull coating

The performance was considered in two areas: performance categories and missions.

The performance categories tend to mirror the categories of full scale trials and an attempt was made to focus the

answers on these categories. In practice, this was difficult as the ships rarely operate in any one category for an extended period. The performance categories were:

Level ice  
Ridges  
Broken Ice  
Manoeuvring  
Pressured Ice  
Transit  
Propulsion System  
Open Water

The vessel was designed to carry out various mission roles. The ships in the study were designed for the following missions:

Towing  
Anchor Handling  
Ice Escort  
Supply

The mix of the missions in the design of each of the vessels was different and this is reflected in the ability of the ship to perform a lower priority mission.

The masters interviewed for this study, along with the ship which they represented, were:

|                |               |                            |
|----------------|---------------|----------------------------|
| C. Cunningham  | Kigoriak      | Canmar                     |
| W. Prucklmeier | Robert Lemeur | Canmar                     |
| P. Kimmerly    | Terry Fox     | BeauDril                   |
| J. Hurt        | Ikaluk        | BeauDril                   |
| S. Wiseman     | Arctic Ivik   | Arctic Transportation Ltd. |

The questionnaires also asked a variety of questions to further the understanding of the vessels capabilities and limitations. These included:

- Limits of performance due to environmental and design features.
- Ranking of other vessels with which the master was familiar.
- Changes to the present vessel to improve the performance.
- The importance of sub components of the performance category in the evaluation of the vessels' performance (eg. how important are ahead vs. astern performance in level ice).

The results of these questions are discussed fully in Appendix A and it is not the intent to discuss them further in the present study. The emphasis will be placed on the ability

to perform the assigned mission role and the evaluation of the design features.

### 3.2 Role of Design Features on Performance

#### **3.2.1 Introduction**

Other than during trials, the conditions in the performance categories are rarely met for extended periods. In this section, an attempt is made to simplify, by looking at performance categories and design features individually (see Table 3.1). This simplification leads to a better understanding of the importance of each of the design features.

**TABLE 3.1**

#### **Performance Categories and Design Features**

| <u>Performance Categories</u> | <u>Design Features</u>           |
|-------------------------------|----------------------------------|
| Level Ice                     | Bow Shape                        |
| Ridges                        | Bow Wedge                        |
| Broken Ice                    | Stern Shape                      |
| Manoeuvrance                  | Propeller Arrangement            |
| Pressured Ice                 | Reamers                          |
| Transit                       | Length of Parallel               |
| Hull Coating                  | Mid-body                         |
| Propulsion System             | Sloped Midship Side              |
| Open Water                    | Auxiliaries (friction reduction) |

#### **3.2.2 Level Ice**

Performance in level ice is the main criteria which is used to judge the performance of different ships. In practice, level ice without ridging is rarely met. However, the level ice performance is an established criteria for evaluating a vessel's overall performance in ice. In the following sections, the role of the design features on the performance in level ice is discussed, based on an analysis of the answers given by the 5 masters (see Section 3.0 Appendix A).

##### **Bow Shape:**

All of the bow shapes are effective in level ice. Without the quantification of performance from full scale ice trials, it is not possible from the interviews to conclude what effects the bow profile angle and section angle have on performance.

However, several comments on the bow of the Robert Lemeur lead to a better understanding of bow design for level ice-breaking. The bow of the Robert Lemeur is considered to offer the lowest resistance in level ice. However, it pushes ice down under the ship, which in shallow water may interact with the bottom of the ship and the sea floor. The flat sections of the Robert Lemeur's bow allow the bow to follow the path of least resistance, making course keeping difficult. The other bows have a clearly defined stem shape and directional stability in ice was not mentioned as a problem.

#### **Bow Wedge:**

As the wedge is underwater, its role is difficult to determine from observation alone. However, with knowledge of the type and dimensions of the wedge and other observations, the role of the wedge can be inferred. On the Terry Fox, Robert Lemeur and Arctic Ivik, the track is clearer than on the other ships (Kigoriak and Ikaluk). The wedges on the former ships are wider and deeper than on the latter two ships. From observations of the Terry Fox, it would appear that the wedge is only effective in keeping the wake clear at lower speeds. As the wedge pushes the ice aside, it also plays a role in keeping ice out of the propeller and from the centre of the flat bottom. This is difficult to quantify as other factors (such as the stern wedge on the Robert Lemeur) influence this.

#### **Reamers:**

In level ice, the reamers provide an area with reduced ice contact along the ship's side. This reduces friction in the mid-body area. The role of reamer width is not quantifiable from the observations, although on the Kigoriak it was observed that the reamer should be wider when operating in multi-year ice to reduce the amount of mid-body/ice contact.

#### **Length of Parallel Mid-Body:**

It was not possible to quantify the effects of this feature on performance in level ice, other than in conjunction with the reamers above.

#### **Stern Shape/Propeller Arrangement:**

All of the ships have square sterns for anchor handling and/or supply duties. They all have different underwater shapes ranging from the skirt of the Robert Lemeur to the shallow V shape sections of the Kigoriak, Miscaroo and Terry Fox. The ships have varying degrees of undercut stern. For some ships the length of the under cut is dependent on the draft. In addition, the ships have different clearances above the propeller/nozzle for ice to pass by. The propeller arrangements vary from a single centreline nozzled propeller on the Kigoriak to a twin open screw arrangement on the Terry Fox.



The nozzle of the Kigoriak is considered least protected against ice entering it. When breaking ice ahead, the nozzle of the Kigoriak suffers from little blockage until the ice thickness exceeds 1.5m. This is due to a combination of bow shape, rise of bottom, stern shape and the centreline propeller. All of the other ships have minimal ice propeller interaction when breaking ice ahead.

The common denominators in achieving good astern performance appear to be the ability to break the ice before it contacts the underwater appendages, and the capability of the ice to flow past the stern and propellers/nozzles with minimal interference.

All of the ships have poor astern performance as they push ice behind the ship. This tendency is decreased on the Terry Fox at shallower drafts when the V shape of the stern, combined with above propeller clearance, is exposed allowing the ice to pass by more readily. The shape of the skirt on the Robert Lemeur protects the propellers from ice interaction astern, but severely curtails astern performance due to the wedging action (ie. the ice is pushed aside, not down). The ships with exposed nozzles (Kigoriak and Miscaroo) suffer from blockage astern. On the Arctic Ivik and Robert Lemeur, with aft end hull forms protecting the nozzles, this blockage is minimal. The open propellers of the Terry Fox digest the ice and keep the ice moving past the stern (ie. no blockage of nozzles), but at the expense of propeller/ice interaction with multi-year ice when going astern. The ability of the hull forms to prevent blockage is dependent upon the ice thickness to draft ratio (Arctic Ivik).

#### **Auxiliaries for Friction Reduction:**

The water wash systems on the Kigoriak and Robert Lemeur are effective in reducing friction at all speeds. They are considered most beneficial in conditions such as cold temperature (<-20°C) and deep snow cover.

The bubbler on the Terry Fox is effective at low speeds in thick ice conditions when the vessel is approaching its limits of performance.

The air/water bubbler on the Ikaluk and the underwater wash and bubblers on the Robert Lemeur using higher pressure appear to be ineffective.

#### **Hull Coating:**

A low friction intact coating (Inerta 160 on all ships in this study), especially in the bow region, is essential for good performance. This has been demonstrated by the deterioration of the performance of the Kigoriak as the bare steel hull became corroded. Coating the hull with Inerta restored the performance to better than new. This applied to both the resistance ahead and extraction of the ship.



### 3.2.3. Ridges

Effective and efficient performance in ridges is the major determinant in the average speed of a vessel transiting a mixed regime of level ice and ridges. Assuming multiple rams for full ridge penetration, a ram cycle in ridges is composed of four distinct phases;

- 1) acceleration in channel
- 2) impact and penetration
- 3) extraction
- 4) backing in channel

Deficiencies in performance in any phase can add considerably to the ram cycle time and reduce transit speed. The following sub-sections describe the importance of the vessel design features in the determination of good ridge performance.

#### **Bow Shape:**

It is not possible from the interview to quantify the effects of bow shape on ridge penetration due to the many variables for both the ships in this study and the characteristics of the ridge. The variables for the ships include bow profiles and section shapes, displacement and power. The variables for the ridge include ridge depth, degree of consolidation, ice strength, snow cover, etc. Quantification of ridge performance can only be done under controlled conditions with known ridge properties.

However, certain bow characteristics do contribute to effective ridge performance. A V shape forward, even if very flat, ensures that the vessel will hit the required location and not slide sideways due to an oblique hit on an uneven ice contour. The flat centreline shape of the Robert Lemeur offers little lateral resistance and the vessel will tend to slide sideways in an oblique hit, dissipating the ship's ridge penetration energy. The bows of the ships in this study produce high vertical loads with little wedging action. This is effective in floating ridges, but may reduce the performance in grounded ridges (per C. Cunningham - Kigoriak) as this type of ridge must be broken apart by pushing it aside rather than breaking it down.

The shape of the bow also contributes to ease of extraction. Although no ship in this study was cited as having difficulty in extraction, the master of the Kigoriak commented in particular on the ease of extraction.

#### **Bow Wedge:**

The role of the wedge in ridges is twofold:

- 1) to stop the ship before it beaches
- 2) to crack the ice and clear it aside

All of the wedges are effective in stopping the ships before they beach. However, the location of the wedge (distance aft of the bow and below the waterline) and its shape (opening angle and profile) are critical in the manner in which it acts and its effectiveness. The wedge on the Kigoriak is too blunt and vertical as it stops the ship very abruptly with high accelerations. In addition, it does not clear and crack the ice as effectively as the Terry Fox. The changes in shape to the Robert Lemeur's wedge, as learned from experience with the Kigoriak, allow the ship to stop gradually. However, the wedge is too far aft, as it does not prevent the ship from sliding sideways in an oblique hit (see bow shape above). For some conditions, the wedge on the Arctic Ivik is too far forward. It stops the ship before the full effect of the vertical bow force can be brought to bear on the ridge.

#### **Reamers:**

The reamers fitted on the Kigoriak and Robert Lemeur create a hole through the ridge wider than the mid-body of the ship. This should reduce the friction on the mid-body if a clear hole were created, but the ice can collapse behind the reamer causing difficulty in extraction. The captains of these ships exercise caution in ramming by widening the hole in the ridge. However, this is also the practise of the masters of the other ships when ramming large ridges, as mid-body friction, becomes high once fully in the ridge. The location of the reamers relative to the bow is also critical. In some circumstances, the reamers of the Robert Lemeur may hit the ridge before the bow which reduces effective ridge penetration, if approaching the ridge obliquely.

#### **Length of Parallel Mid-Body:**

This feature was not specifically identified as a problem although, as mentioned above in reamers, high mid-body friction can reduce the performance.

#### **Stern Shape and Propeller Arrangement:**

As in level ice performance, the key issues are:

- 1) Performance astern
- 2) propeller ice interaction

The square stern of these vessels tend to push the ice in the channel behind the ship, decreasing the ability to go astern for the next ram. This may manifest itself as either slow astern speed and/or minimal backing distance before the ship is stopped.

If the nozzles suffer from blockage (especially on the Kigoriak and Ikaluk), the time required to clear the blockage by reversal of thrust or aborting the acceleration run adds time to the ram cycle and degrades the overall transit performance. The reversal time of thrust also becomes then very important.

#### **Auxiliaries for Friction Reduction:**

Low friction is essential for good extraction. The water wash on the Kigoriak is only used in high friction conditions (deep snow cover, cold, hard ice), but is not considered essential for the majority of ridge ramming. Because of the shallower stem angle of the Robert Lemeur, the water wash is used more frequently than on the Kigoriak. The air bubbler on the Terry Fox improves the extraction capability, but the air/water system on the Ikaluk is ineffective.

#### **Hull Coating:**

A good low friction high impact performance coating is essential, to avoid the roughness of a corroded bare steel.

#### **3.2.4 Broken Ice**

Broken ice is encountered when the ship has to negotiate a previously broken channel or navigate through an area of ice broken by wind and current. The ice may be consolidated. The extent of consolidation will depend upon the temperature and length of time since the ice was broken.

Because of the extreme variability of the broken ice conditions, quantification of performance in the regime is difficult unless trials are conducted under controlled (vessel speed and power) and measured (ice size pieces, degree of consolidation, etc.) conditions.

The following sub-sections indicate the role of various design features in the determination of good broken ice performance.

#### **Bow Shape:**

For the ships in the present study, the bow shape does not appear to influence the performance. The wide blunt waterline shape of the Robert Lemeur tends to push ice ahead of the ship before the ice submerges.

#### **Bow Wedge:**

The wedge plays a role in clearing the ice to the side and leaving reduced concentration in the wake. The wide deep wedges of the Robert Lemeur, Terry Fox and Arctic Ivik are effective in a channel, although less so in rubble. The wedge on the Ikaluk is less effective due to its reduced depth at

the ship's side. The Kigoriak's wedge is only 3m wide and is not effective.

#### **Reamers:**

The reamers do decrease the friction on the parallel mid-body in broken ice. In addition, the wider reamers of the Kigoriak minimize multi-year ice interaction with the side shell.

#### **Length of Parallel Mid-Body:**

This design feature was not specifically identified as a concern.

#### **Stern Shape and Propeller Arrangement:**

The issues here are common to the previous performance categories, namely astern performance and propeller/ice interaction. The comments are similar to those for level ice performance. The stern shapes and propeller locations of the Robert Lemeur and Arctic Ivik are particularly effective in keeping ice out of the propellers.

#### **Auxiliaries for Friction Reduction:**

Except under high friction conditions (snow cover and mush ice) the range of hull lubrication systems are not used in broken ice. On the Ikaluk, although the high pressure underwater lubrication system is not effective in higher friction conditions, it is effective in pushing ice aside in less than 10/10 cover.

#### **Hull Coating:**

In unconsolidated ice, the ice tends to be well lubricated and high friction is not a problem. However, in consolidated ice, a good low friction coating becomes important.

### **3.2.5 Manoeuvring**

Manoeuvring in ice is divided into the following components:

- turning ahead
- turning astern
- channel breakout
- channel widening

Good manoeuvrability is a prerequisite for fast transit as it enables the ship to avoid large ridges and other ice features which would reduce the average speed. Manoeuvrability is also a vital component of successful ship escort and supply.



The discussion in the following sub-sections provides details of the role of the design features in providing good manoeuvrability.

#### **Bow Shape:**

Other than when heeled, the role of the bow in manoeuvring ahead is not quantifiable from observation aboard the ship. The Kigoriak and Robert Lemeur have both used heel as a means of reducing the turning circle diameter. The different sections of these bows have produced differing results. The Kigoriak clearly showed a reduced diameter when heeled in the direction of the turn. The Robert Lemeur had smaller turning circles when heeled but mixed results depending upon the angle of heel (see Section 3.0 for a discussion of full scale trial results).

The ahead component of the star manoeuvre, and channel breakout involve similar considerations, ie. the ability to break into unbroken ice from a broken channel. The flat sections of the bows of the Kigoriak and Robert Lemeur allow the ship to break out of the channel early. This is more difficult with the more pronounced V shaped sections of the Terry Fox and Ikaluk. Once into the unbroken ice, the V shaped section ensures that the ship will stay there. The completely flat centreline shape of the Robert Lemeur sections may allow her to slide back into the old channel. The Arctic Ivik has similar tendencies to the Robert Lemeur.

Channel widening involves either widening the track by at least  $1/2 B$  by running the ship in unbroken ice on a parallel course to the existing track or resting the transom on one side of the broken channel and running the ship crabwise down the channel. The first method requires good directional stability, which seems to be best met with the ships with some V shape to the bow sections (Terry Fox and Kigoriak). However, if the V is too steep, the ship will tend to be deflected back into the old channel (eg. the Ikaluk). With poor directional stability (the Robert Lemeur) the ship will follow the path of least resistance (ie. cracks) back into the old channel. The second method involves an equilibrium between the forces of the rudder and the ice on the transom versus the lateral component of the icebreaking force at the bow. The bow section angles of the Kigoriak create low lateral ice forces. This enables her to readily perform this method with few instances where she slides back into the old channel.

#### **Reamers:**

The reamers allow the stern to swing out in a broken channel, allowing the bow a more favourable angle for turning ahead and channel breakout. The wider reamers of the Kigoriak are more effective than the narrower reamers on the Robert Lemeur. The shape and position of the reamers is also impor-

tant as ice occasionally gets caught on the inboard reamer which impedes the turn.

#### **Length of Parallel Mid-Body**

The longer the mid-body length and the further aft the length is carried (ie. minimal or no stern cutaway), the greater the difficulty in turning. The Ikaluk is the prime example of this as the parallel mid-body extends almost to the stern. A short mid-body length allows the ship to swing in the channel for more favourable bow approach angles for breakout and turning. The cutaway sterns of the Terry Fox and Arctic Ivik are of some assistance, but they still leave a long parallel midbody.

The width of reamer and length of parallel mid-body must be balanced for good manoeuvrability. The Kigoriak is good, whereas the reduced width of the Robert Lemeur's reamer coupled with the increased length of the mid-body reduce the turning performance.

#### **Sloped Midship Sides:**

Kigoriak, Robert Lemeur and Arctic Ivik have vertical sides. Such sides can not break or displace ice.

Terry Fox and Ikaluk have 8 degrees midbody slopes. This angle is too small for the operator to notice any discernable improvement to turning performance.

#### **Stern Shape and Propeller Arrangement:**

The square sterns of these ships impede the ability to manoeuvre astern as they tend to push ice aft of the ship. This is mitigated somewhat by the cutaway sterns of some of the ships (ie. Kigoriak, Robert Lemeur, Terry Fox and Arctic Ivik). The flared section shapes on the transom of the Kigoriak's stern offers very little lateral resistance. With the rudder amidships and no available differential thrust from the single screw, she tends to break out of a channel when going astern due to any wind or unsymmetry in the channel. Although the cutaway stern of the Robert Lemeur allows the ship to swing in a channel, the degree to which she can swing is limited by the vertical skirt contacting the unbroken ice edge. The sterns of both the Robert Lemeur and Arctic Ivik offer good protection from propeller/ice interaction in a turn.

The exposed nozzled propellers of the Kigoriak and Ikaluk suffer from increased propeller/ice interaction when turning as do the open propellers of the Terry Fox. In the former ships, the result is increased incidence of blockage, whereas in the latter, it is increased risk of damage with multi-year ice.



Manoeuvring astern is accomplished with differential thrust on the ships with two propellers, as the rudder is generally centered for protection from ice interaction. The propellers of the Robert Lemeur are too closely spaced for effective differential thrust.

The use of differential thrust for manoeuvring when going ahead for the twin screw, twin rudder ships is counter-productive as the effectiveness of the rudders is lost.

#### Auxiliaries for Friction Reduction and Hull Coating:

The level ice comments regarding the auxiliaries are applicable here. The higher the speed in a turn the tighter the turning radius. Reduction of friction is, therefore, important for reduced turning circles.

### 3.2.6 Pressured Ice

This is the most difficult performance category to deal with as the degree to which the ice is pressured has, to date, only been inferred from subjective observations. These observations include:

- how quickly the track closes
- wind speed and direction
- current speed and direction
- increase in power level required to maintain same ahead speed as with no pressure

Pressure is primarily an issue of increased friction on sides. All of the ships in this study have been stopped by pressure in conditions which would present no difficulty if the ice were unpressured.

As pressure occurs in ice, many of the comments that apply for broken ice are applicable here. The comments in the following sub-sections are indications of how the design features influence the performance in pressured ice.

#### Bow Shape:

The short bows of all the ships in this study reduce the length of pressured ice in contact with the ship when the ship is heading into the direction from which the pressure is coming. This reduces the overall friction and may be the only direction in which the ship can maintain forward progress.

#### Reamers:

The reamers reduce the length of mid-body contact with pressured ice and limit the effect of pressure.

### **Length of Parallel Mid-Body**

The longer the length, the greater the friction, especially when travelling at right angles to the pressure direction.

On the Arctic Ivik it was felt that the combination of long parallel mid-body and stern shape keeps the area clear immediately aft of the ship, making it possible to go astern.

### **Sloped Midship Sides:**

This is the only performance category in which this design feature was mentioned. The master of the Terry Fox felt the sloped sides on his low freeboard ship were beneficial in keeping ice off the deck in highly pressured ice conditions.

### **Stern Shape and Propeller Arrangement:**

The issues are common to the previous performance categories:

- astern performance with a square stern
- propeller/ice interaction - blockage and protection

In heavily pressured ice, the open propellers of the Terry Fox digest ice without the clogging and reduced thrust which is prevalent with nozzled propellers.

In heavily pressured ice, the aft end shapes of both the Robert Lemeur and Arctic Ivik are no longer as effective in preventing ice/propeller interaction.

### **Auxiliaries for Friction Reduction:**

Only the water wash on the Robert Lemeur and the bubbler system on the Terry Fox are used in pressured ice.

### **Hull Coating:**

As pressure is primarily an issue of increased friction, a good low friction coating is essential for good performance.

### **3.2.7 Transit**

Although transit was listed in the questionnaire as a performance category, it became obvious from the results of the questionnaire that it should be treated as a mission role. It was not obvious from the results how design features specifically related to transit performance. Transit is a mix of the other performance categories as follows:

- level ice
- ridges
- broken ice
- pressure
- manoeuvring
- propulsion
- open water

The percentage of each in transit will depend upon the following factors:

- time of year
- weather
- route
- ice conditions

The role of the design features in transit must, therefore, be correlated with the weighting of each of the performance categories in the make-up of the intended transit.

### **3.2.8 Propulsion System**

Although not strictly a performance category in the same sense as the different categories of ice and open water performance, the performance of the propulsion systems may be affected by each of the design features of interest in the present study. It was, therefore, treated in the same manner. The major issue here is the effect of each of the features on the amount and type of propeller/ice interaction. This interaction is translated into loads on the propulsion system, the magnitude and frequency of which will determine the design and operating conditions of the propulsion system.

#### **Bow Shape and Bow Wedge:**

The bow shape and bow wedge and, to some degree, the mid-body shape (particularly the rise of floor of the Kigoriak midbody) play a role in determining the flow of ice towards the propellers. However, from observations aboard the ships, these effects are not readily observable. In addition, the aft end shape (in particular, the stern ice island on the Robert Lemeur) complicates the issue. The wedge on the Terry Fox is judged to be more effective in pushing ice aside than that of the Ikaluk.

#### **Reamer and Length of Parallel Mid-Body:**

No discernable effect.

#### **Stern Shape and Propeller Arrangement:**

The ships are broken down into three broad categories as regards aft end configuration and propeller arrangement.

- nozzled propellers with little hull protection (Kigoriak and Ikaluk)
- nozzled propellers with hull protection (Robert Lemeur and Arctic Ivik)
- open propeller (Terry Fox)

In the first category, the nozzles protect the propellers from interaction with large pieces of multi-year ice. However, they suffer from blockage which causes long duration loads of large magnitudes and degrades the ship performance due to loss of thrust. The centreline single propeller on the Kigoriak and the clearance above the nozzles and stern shape of the Ikaluk reduce the frequency of blockage as they keep the propellers away from the majority of the ice flow.

In the second category, the aft end shape minimizes the amount of propeller/ice interaction. Blockage occurs infrequently and only under severe conditions (ie. deep ridges, pressure ice and deep rubble fields). In this case, blockage and clogging, with the associated loss of thrust, will occur.

The aft end of the Terry Fox has good clearance above the propellers, which, in the majority of ice conditions, ensures that the ice will flow above and clear of the propellers for minimal ice interaction. In severe conditions, such as pressure and deep ridges, the open propellers digest the ice, with no major loss of thrust. Hence, the open propellers do not suffer from blockage and clogging to the same degree as the nozzled ships. However, the open propellers are subject to higher ice loading as they can contact larger pieces of multi-year ice than nozzled propellers.

#### **Auxiliaries for Friction Reduction:**

In general, when using the auxiliaries, no effect is discernable on the amount and severity of propeller/ice interaction. However, if the increased power required to operate the auxiliary is not compensated by a increase in performance greater than the increase in performance due to an equal level of power applied to the shaft(s), then the system is not economical. The Ikaluk's water jet system has no net benefit in any conditions. The air bubbler system of the Terry Fox is only effective at low speeds in thick ice.

#### **3.2.9 Open Water**

The ships in the present study are limited to operation in the Beaufort Sea. With its limited fetch, the waves do not build to big significant heights. Their short crested nature coupled with high wind speeds occasionally require good seakeeping abilities in the summer months. Manoeuvrability in open water is essential for the supply and anchor handling



mission roles. The discussions in the following sections concentrate mainly on the penalties on open water performance caused by the design features.

#### **Bow Shape, Bow Wedge and Reamers:**

Lacking good full scale speed and powering information and a base ship standard, the role of these features in open water resistance is not readily quantifiable from observation alone.

The role of these features, in particular bow shape, is observable from performance in waves.

The bows of the Arctic Ivik and Ikaluk are good for service in the Beaufort Sea, suffering to a lesser degree from wetness and pounding than the other ships in this study.

The Terry Fox and Kigoriak suffer from wetness. The bows of the Robert Lemeur and, to a lesser degree, that of the Kigoriak with shallower section shapes suffer from pounding and slamming.

In the Robert Lemeur, the transition from the sloped to vertical profile of the bow causes slapping of the waves as the transition is too close to the water. This affect is ameliorated by stern trim.

#### **Parallel Mid-Body and Sloped Midship Sides:**

No noticeable effect of these features. The hard chined midbody shape of all the ships helps to reduce severity of roll.

#### **Stern Shape and Propeller Arrangement:**

The low freeboard aft can be a problem in open water due to deck wetness in waves. This occurs primarily on the Terry Fox and Kigoriak.

The nozzles give good low speed thrust for low speed towing and good acceleration.

As in ice, wide spacing of the propellers off the centreline is essential for good differential thrust for low speed manoeuvring. In addition, the 4 ships with rudders in the propeller wake are far better at low speed manoeuvring than the single centreline rudder on the twin screw Terry Fox.

#### **Auxiliaries for Friction Reduction:**

Not used in open water for this purpose. The bubbler on the Terry Fox is effective as a cushion when approaching docks or other vessels.



### **Hull Coating:**

The hull coating must be kept in good condition to avoid the severe corrosion which can occur in the Beaufort Sea. As demonstrated on the Kigoriak, this can lead to a severe deterioration of open water performance, estimated 2 knots drop in open water speed. Only a high impact abrasion resistant coating such as Inerta 160 can withstand the ice damage and remain intact for the open water season.

### **3.3 Mission Roles**

#### **3.3.1 Introduction**

Table 3.2 summarizes the ability of each of the ships in the study to perform their mission role. All of the ships are able to perform their mission roles, all with varying degrees of success. A discussion of the ranking in the table is given in the following sections.

#### **3.3.2 Ice Management**

Ice management is carried out in two different ways; breaking up the floes and pushing the floes. Breaking up the floes requires a combination of the following factors:

- 1) High power to displacement ratio for fast acceleration in high ice concentrations.
- 2) A strong ship primarily in the bow.
- 3) Bow form and displacement to split the floe.
- 4) Manoeuvrability to turn quickly in high ice concentrations.

Both the Kigoriak and the Terry Fox are very successful in breaking apart floes as they exhibit these characteristics in large measure. The Kigoriak has two deficiencies: blockage of the nozzle and a bow wedge that stops the ship too abruptly and reduces the splitting efficiency. The single centerline rudder, on the Terry Fox, degrades the manoeuvrability.

The Ikaluk has poor manoeuvrability in high ice concentrations due to the length of parallel mid-body and the nozzle blockage which limits performance.

Both the Robert Lemeur and the Arctic Ivik are underpowered for aggressive floe breaking. The bow of the Robert Lemeur is very flat and tends to slide off if the floe is hit obliquely. The Arctic Ivik is only a class 2 and is not designed for this duty in thick ice and therefore is not strong enough for breaking apart large floes.

To successfully push a floe requires a combination of bow shape and thrust. The bow of the Terry Fox tends to break the floe rather than push it. The Robert Lemeur's bow allows the ship to slide off if not positioned at right angles.

The abilities of the ships reflect the primary role that they play in ice management. The Kigoriak and the Terry Fox are larger ships and are used to aggressively break up large floes. The Ikaluk is used for both pushing and breaking. The Arctic Ivik is used primarily for pushing while working with the larger, more powerful ships.

The Robert Lemeur, in comparison to other Canmar ships, does little ice management.

### 3.3.3 Towing

Successful towing is dependent upon towing equipment and power.

Both the Kigoriak and the Terry Fox are well equipped with towing winches and are powerful.

The Arctic Ivik has good equipment, but suffers from lack of power for the larger tows.

The type and location of equipment on the Ikaluk makes towing more difficult.

The Robert Lemeur is not equipped with towing equipment.

### 3.3.4 Anchor Handling

The primary factors in successful anchor handling are:

- 1) Equipment and deck layout.
- 2) Low speed manoeuvrability, and station keeping.
- 3) Protection of propellers from cables.

The Kigoriak, Ikaluk and Arctic Ivik all have nozzles and have the propellers well protected. These ships have good low speed manoeuvrability and are well equipped. The 20 tonne crane of the Kigoriak is especially beneficial in handling anchors. The Ikaluk has a relatively ineffective bow thruster and, hence, suffers in station keeping and low speed manoeuvrability.

The open screws of the Terry Fox are exposed to anchor wire contact. In addition poor low speed manoeuvrability due to the single centerline rudder between the wing propellers degrades the performance.

### 3.3.5 Ice Escort

The vessels being escorted are generally of a much lower ice class and, hence, benefit from a wide clear track. In severe ice conditions, the escorted vessel may become stuck and require assistance from the icebreaker. Manoeuvrability, especially the ability to back down on the escorted ship, then becomes important. The ability to widen an existing channel is important for escorting a ship wider than the icebreaker (ie. a drill ship).

The track of the Kigoriak is not as clear as that of the other ships.

All the ships, with the exception of the Kigoriak, are twin screw and, hence, are able to manoeuvre astern using differential thrust, despite the square sterns which limit the astern capabilities.

The Ikaluk tends to fall back into the old track when widening a channel and, hence, the ranking is lower.

### 3.3.6 Supply

The success of the supply role depends upon the following factors:

- 1) Cargo deadweight
- 2) Deck area and equipment
- 3) Transit ability in mixed ice regimes
- 4) Low speed manoeuvrability

The cargo deadweight of the Robert Lemeur, Ikaluk and Arctic Ivik are very good as are the deck equipment and deck area. The Arctic Ivik has an especially good deadweight on a low draft.

Both the Kigoriak and the Terry Fox require improvements to the bulk handling systems to improve their ranking.

All the ships have good transit capabilities, with the larger ships very effective in severe ice conditions when their high powers and displacements ensure high transit speeds, especially in ridging. The low aft freeboard of the Kigoriak is a problem when heavily loaded as ridge ramming can flood the after deck.

The Robert Lemeur has poor directional stability at low speeds which makes the approach to the rig difficult. The lack of effective thrusters on the Ikaluk makes station keeping alongside the rig difficult.

### 3.4 Conclusions

The conclusions fall into three categories:

- 1) The validity of the questionnaire process
- 2) The role of the design features in the determination of vessel performance
- 3) The ability of the various vessels to perform their assigned mission roles

#### 3.4.1 Questionnaire Process

The questionnaire has proven its worth as valuable qualitative information about vessel performance features and the ability to perform the mission roles was obtained. This information complements and supports the full scale results. Moreover, there was general consensus amongst the five interviewed captains about the role of the design features.

#### 3.4.2 Role of Design Features

The qualitative assessment of the role of the design features on performance is summarized in the following subsections.

##### Bow Shape:

- all the bows are effective in level ice
- bows with a moderate V shape offer good directional stability in both level ice and ridge breaking
- bows with flat sections are able to break out of channels readily, but suffer from poor directional stability
- bows with more extreme V shape are difficult to break out of channels
- the short bows of the ships in this study are good in pressured ice
- all the bows are less than ideal for extreme open water conditions, with the flat section, shallow stem angle bows the worst.

##### Bow Wedge:

- blunt angle wedges with vertical profiles cause high decelerations in the ridges
- if the wedge is too far forward, the vessel is stopped before the effective vertical icebreaking force can be developed
- if the wedge is too far aft, the lack of contact of the wedge coupled with flat sections allow the ship to slide sideways in an oblique ridge impact, reducing the breaking effectiveness

- wide, deep bow wedges are more effective than shallow, narrow wedges in clearing ice from the wake and the propellers
- at higher speeds the effectiveness of ice clearing is reduced

#### Reamers:

- are effective in reducing midbody friction, especially in pressure ice and level icebreaking
- assist in manoeuvring by providing space for the stern to swing, but the width must be considered in conjunction with the length of parallel midbody
- if overly aggressive in ridges may cause the ship to become jammed

#### Length of Parallel Midbody:

- excessive length compromises manoeuvring and increases the friction in pressured ice and ridges

#### Stern Shape and Propeller Arrangement:

- the astern performance of all the ships is generally poor
- Stern cutaway enhances the manoeuvrability
- clearance above the propeller is essential to minimize the ice/propeller interaction
- a shallow angle stern section shape permits the vessel to manoeuvre astern
- nozzled propellers protect the propeller from interaction with large pieces of multi-year ice, but performance is degraded by blockage
- skirts and aft wedges are effective in reducing propeller/ice interaction, but can degrade astern performance and manoeuvrability
- open propellers maintain effectiveness in conditions with a great ice thickness (ridges, broken or pressure ice) as they suffer from less thrust degradation than nozzle propellers. However, in multi-year ice, due caution is exercised by the masters in order to prevent damage
- in low speed manoeuvres, typical of extreme icebreaking, the rudder is most effective directly behind the propeller(s)
- single propellers, although less vulnerable due to their centerline location, do not provide astern manoeuvrability

#### Sloped Midship Sides:

- the angles of the midship sides of the ships in this study (8 degrees) are too small to observe any benefit in pressure ice or when manoeuvring.



#### Auxiliaries for Friction Reduction:

- the bow water wash is universally effective
- the bubbler is effective only in limiting conditions (ie., thick ice and low speed)
- they must be located at the bow
- only effective if the power input into the auxiliary produces a bigger benefit than an equal power input to the main propulsion system

#### Hull Coating:

- an effective, intact coating is essential for effective icebreaking

#### 3.4.3 Mission Roles

The ships in the study have operated beyond their design ice class. all have been able to perform their assigned mission roles despite obvious deficiencies in backing and turning performance when compared with conventional icebreakers. The captains have capitalized on the vessels superior ahead level icebreaking performance and utilized alternatives such as Star or Captain's manoeuvres to overcome the astern deficiencies.

TABLE 3.2

## ABILITY OF SHIPS TO MEET MISSION ROLE

1+ EXCEPTIONAL      1 GOOD      0 ACCEPTABLE      -1 DEFICIENT      -1- UNACCEPTABLE

| MISSION         | KIGORIAK | ROBERT LENEUR | TERRY FOX | IKALUK | ARCTIC IVIK |
|-----------------|----------|---------------|-----------|--------|-------------|
| ICE MANAGEMENT  | 1+       | 0             | 1+        | 1      | 1           |
| TOWING          | 1+       | N/A           | 1+        | 1      | 1           |
| ANCHOR HANDLING | 1+       | N/A           | 0         | 1      | 1           |
| ICE ESCORT      | 0 TO -1  | 1             | 1         | 0      | 1           |
| SUPPLY          | 1        | 1             | 1         | 0      | 1+          |



#### 4.0 LEVEL ICE PERFORMANCE AHEAD

##### 4.1 Full Power Performance, Speed versus Ice Thickness, Winter-Spring/Fall

###### 4.1.1 General

The plots of full power performance ahead of the ice-breakers in level ice without any hull lubrication systems operating are shown in Figure 4.1.1, Winter and Figure 4.1.2, Spring/Fall. Tabulation of the data points with source references are given in Table 4.1.1 (D)\*, Winter and Table 4.1.2 (D), Spring/Fall. All data are for the vessels at icebreaking drafts as given in Section 2.1.

As stated in Section 2.2, Winter conditions are characterized by an air temperature of below -20 degrees C, a snow cover of at least 3 cm and associated high ice strength. Similarity of ice strength properties is demonstrated from an analysis of flexural strength based on temperature and salinity profiles, and of compressive strength from borehole jack measurements. The Winter tests on Kigoriak, Robert Lemeur, Terry Fox and Ikaluk were carried out between December and April in the Southern Beaufort Sea.

The specified Winter conditions are considered representative for mid-Winter operations in the Canadian Arctic.

The performance data for Max Waldeck must be treated with caution since they were obtained in warmer temperatures and in lower salinity conditions of the Baltic. It would appear that the ice strength properties lie somewhere between Canadian Arctic Winter and Spring/Fall conditions.

Spring/Fall ice conditions are characterized as follows:

- ice conditions during the degradation process in the Beaufort Sea before break-up of landfast ice takes place. Normally mid May to July.
- decayed heavy first year ice in the higher Arctic before re-freezing occurs. Normally August and September.

The ice strength data in Section 2.2 show clearly the weaker and more variable nature of the ice conditions in the Spring/Fall as against the Winter period.

\* (D) denotes Table/Figure found in Appendix D

The Spring/Fall category is fairly broad in scope, but is considered the only practical way of grouping the various trials data. Again, results for Max Waldeck must be treated with caution since Baltic ice conditions differ from those in the Arctic.

The plots of full power performance give a measure of the ability of the vessels to transit level ice in Winter and Spring/Fall environmental conditions. One may, therefore, compare the icebreaking abilities of different vessels in Winter or Spring/Fall ice conditions and the icebreaking ability of a particular vessel in Spring/Fall as opposed to Winter conditions. However, these presentations do not specifically indicate the relative level icebreaking efficiency of the vessels or the influence of hull design features on ice transiting performance since, as noted in Section 2, there are also significant differences in size, power and propulsion arrangement between the vessels. The ship performance data must, therefore, be normalized or brought to a common basis of comparison in order for relative efficiency and parametric influence to be addressed. This will be carried out in subsequent sections of this report.

In the following sub-sections, the full power performance data analysis and results are described and key conclusions are drawn.

#### **4.1.2 Data Analysis**

The data are taken from dedicated full scale trials which have historically provided the most reliable source for performance data. They are divided into the two categories, Winter and Spring/Fall as described above.

There is no agreed method of correcting icebreaker performance data for the many physical ice properties influencing the energy expended or power required to transit ice. Nor is it within the scope of this project to develop such a method. Consequently, the separation of trials data into the two categories on the basis of demonstrated similarities in ice strength properties, is adopted as the practical alternative.

As described in Section 2.2, the ice and snow thickness is considered to be measured reasonably accurately and the effect of snow is taken into account by interpreting the snow as an equivalent additional ice thickness of one-half the actual thickness of snow.

The vessel's hull conditions at the time of the trials are addressed in Section 2 and are given in Table 2.3.



The presentation of full power performance ahead of the icebreakers in level ice for Winter and Spring conditions are, therefore, made on the following basis:

- no extrapolation of data beyond full scale tests.
- no correction for ice strength properties. Data are grouped according to Winter or Spring/Fall conditions.
- Inerta covered hulls (plus Kigoriak with base smooth hull).
- no hull lubrication systems operating.
- snow accounted for as an equivalent additional ice thickness of one-half snow thickness.

#### 4.1.3 Results

##### Winter Ice Conditions

Figure 4.1.1 shows how the level ahead icebreaking speed of the vessels reduces approximately linearly with increasing level ice thickness. It is also noticeable that the slopes of the curves for the four largest, most powerful vessels, Kigoriak, Terry Fox, Ikaluk and Robert Lemeur, with low friction hull coating, are all very similar, while those for the two smallest vessels, Arctic Ivik and Max Waldeck, are both equal and considerably steeper. The data for Kigoriak with bare steel hull versus Inerta coating show very graphically the benefit gained in level icebreaking ability through using an effective low friction hull coating. This matter is dealt with in detail in Section 4.6.

Only Kigoriak in the bare hull condition has been tested close to its limiting conditions in Winter Ice. Reliable uniform level ice data for other vessels in the group are limited to a maximum Winter ice thickness of 1.0m.

The most effective vessel in the group in terms of maximum level icebreaking ahead at any speed is the Kigoriak. She is followed by the Terry Fox, which is the most powerful vessel in the group and the only one with open as opposed to ducted propellers. Consequently, the propulsive thrust delivered is lower per unit shaft power than for Kigoriak. Absolute level icebreaking ability is then consecutively lower for Ikaluk, Robert Lemeur, Arctic Ivik and Max Waldeck, coming in the order of reduced installed power.

For the most part, the curves are for constant maximum or near maximum shaft power. In two cases, however, for Terry Fox in particular and also Ikaluk, the open water power is less than that used in thick ice. Open water power is limited because at high open water speeds, the maximum pitch available at the propeller limits the ability of the propellers to absorb power.

The level icebreaking abilities of the vessels at two ahead speeds, 8 knots and 3 knots, obtained from Figure 4.1.1 are given in Table 4.1.3 below.

The 8 knots speed, for which reliable data are available for all vessels, is selected from experience as an operationally efficient transit speed for the larger vessels in the group. At this speed, the vessels would have sufficient energy for efficient penetration of most ridges without extensive ramming, which radically reduces average transit speeds.

The 3 knot speed is used since the normal interpretation of Arctic Class (CASPPR) level icebreaking requirements is for continuous progress at 3 knots in an ice thickness in ft. equal to the Arctic Class. These data are extrapolated from the curves in Figure 4.1.1

**Table 4.1.3**  
Ship Performance in Level Winter Ice

| <u>Ship</u>              | <u>Level</u><br><u>Icebreaking Thickness</u> |                | <u>Arctic</u><br><u>Class</u> | <u>Level</u><br><u>Icebreaking</u>       |
|--------------------------|----------------------------------------------|----------------|-------------------------------|------------------------------------------|
|                          | <u>8 Knots</u>                               | <u>3 Knots</u> |                               | <u>Requirements</u><br><u>at 3 Knots</u> |
| Kigoriak (Inerta)        | 1.10 m                                       | 1.6 m          | 4                             | 1.2 m                                    |
| Terry Fox                | 0.93 m                                       | 1.5 m          | 4                             | 1.2 m                                    |
| Ikaluk                   | 0.84 m                                       | 1.4 m          | 4                             | 1.2 m                                    |
| Robert Lemeur            | 0.67 m                                       | 1.3 m          | 3                             | 0.9 m                                    |
| Arctic Ivik              | 0.44 m                                       | 0.8 m          | 2                             | 0.6 m                                    |
| Max Waldeck              | 0.38 m                                       | 0.75 m         | -                             | -                                        |
| Kigoriak (Bare<br>Steel) | 0.86 m                                       | 1.3 m          | 4                             | 1.2 m                                    |

#### Spring/Fall Ice Conditions

Figure 4.1.2 for level icebreaking ahead in Spring/Fall ice conditions shows the same characteristics as the equivalent Winter results. Far fewer data are, however, available and there is considerable scatter in the results for Terry Fox which include both Spring and Fall data. This is to be expected since ice conditions vary greatly during these periods and the data grouping used of necessity in this study cannot compensate for such differences in environmental conditions. Taken overall, however, the data provide a clear indication of increased ice thickness breaking ability in deteriorating Spring/Fall ice. These data are given in Table 4.1.4 below for 8 knots icebreaking speed.

**Table 4.1.4**  
Winter - Spring/Fall Performance Comparison

| <u>Ship</u>           | <u>Winter<br/>Thickness</u> | <u>Spring<br/>Thickness</u> | <u>% Thickness<br/>Increase</u> |
|-----------------------|-----------------------------|-----------------------------|---------------------------------|
| Terry Fox             | 0.93 m                      | 1.2 m                       | 29                              |
| Robert Lemeur         | 0.67 m                      | 0.77 m                      | 15                              |
| Max Waldeck           | 0.38 m                      | 0.51 m                      | 34                              |
| Kigoriak (Bare Steel) | 0.86 m                      | 1.33 m                      | <u>55</u>                       |
|                       |                             | Average                     | 33                              |

The thickness of Spring/Fall ice which can be broken continuously is, therefore, on average one-third higher than the thickness of hard Winter ice. The effect of Winter versus Spring/Fall Ice Conditions is addressed further, together with the effect of hull condition on icebreaking performance, in Section .4.6.

#### 4.1.4 Conclusions

Separation of the performance data into two environmental groupings, Winter and Spring/Fall ice conditions, is justified by the logical nature and consistency of the resulting comparisons within each set and between each set.

The Winter ice group is far more complete than the Spring ice group. Moreover, the Winter ice group data show less scatter, probably due to the more stable environmental conditions during Winter.

Reliable Winter ice performance data in uniform level ice above 1.0 m is limited to that of the Kigoriak in bare hull condition.

All Arctic Class (CASPPR) vessels in the group clearly perform beyond their Arctic Class requirements using less than Arctic Class formula power.

On average, the vessels in the group can break continuously one-third thicker level ice in Spring conditions than in Winter conditions.

Low friction hull coating results in a very significant improvement in level icebreaking ability over bare, smooth steel.

## 4.2 Power versus Ice Thickness at Constant Speed, Winter

### 4.2.1 General

The full power performance data in Figures 4.1.1 and 4.1.2 are for vessels of different size, at different high power and different relatively high speeds in the full range of level ice test thicknesses. As such, these data are not suitable for determining the relative efficiency of powering performance between the vessels or the effect of design form and features. In order to achieve this, performance data must be presented in a format with fewer variables and at speeds selected to demonstrate particular performance components. Moreover, the most complete and reliable data set is required if meaningful comparisons are to be made.

The approach taken is to present data for Winter ice conditions, corrected to a common vessel size (ie. beam), in terms of power versus ice thickness at constant speed. This form of presentation, as given in Figure 4.2.1 for a speed of 1 m/s, gives a meaningful comparison of the overall powering and hull performance efficiency between the vessels. However, since the vessels have different propulsion arrangements, and in particular the Terry Fox has open propellers whilst the remainder have ducted propellers, presentations such as Figure 4.2.1 do not provide an accurate comparison of hull efficiency in ice. To achieve this and thus determine the effect of hull form and features on icegoing performance, the propulsion element must be removed from the data. This analysis is described in the following Section 4.3, allowing subsequent comparisons to be made on the basis of resistance rather than power. The first step in the process, that of putting the trials data in the format of Figure 4.2.1 is described below.

### 4.2.2 Data Analysis

As in the case of full power performance, the most complete set of level ice performance data for the group of vessels was measured in the more stable and environmentally similar Winter conditions. Most level ice data sets were obtained by testing the vessels in a number of level ice thicknesses, obtaining a speed versus power curve in each case. The data in Figures 4.1.1 and 4.1.2 are simply the highest power data from each of these curves.

Data for Spring/Fall conditions are far fewer with no data for Ikaluk and Arctic Ivik. Moreover, Spring/Fall ice conditions and subsequent test results are shown in Section 4.1 to be more variable than in Winter conditions.



For each vessel and each level test ice thickness, the basic data were interpolated at speeds of 1, 2 and 3 m/s. These data of power versus speed for each vessel in different Winter ice thickness are given in Table 4.2.1 (D).

The data at 1 m/s are considered to provide the most suitable indication of the icebreaking component of level ice-going performance. This speed is considered sufficiently low that the icebreaking and submersion component of total resistance and power will predominate over the ice acceleration or velocity component. These data are, therefore, expected to provide the primary information from which the effect of hull form and features on the icebreaking component of resistance might be deduced.

It was not considered practical to extend the analysis to lower speeds since the percentage accuracy of the data at very low power levels is not considered satisfactory.

The data at higher speeds of 2 and 3 m/s will incorporate an increasing ice acceleration component. Analysis of this power, and subsequently resistance increase, with increase in speed is, therefore, expected to show the influence of design features on the ice clearing component of level icegoing performance.

The effect of vessel size is accounted for by correcting all power data directly proportional with beam to a common beam. Kigoriak's beam of 19.25m was selected as the standard since more data were available for this than any other vessel in the group.

The effect of beam upon icebreaking resistance and power is the best understood of all ship parametric influences, ice-breaking resistance for geometrically similar vessels of different size being very closely directly proportional to beam. In the case of the generally small corrections required in this analysis, errors in correcting linearly for beam are insignificant.

In correcting for the influence of beam in this manner one is essentially comparing the icegoing power of six ice-breakers which are all geometrically similar to their parents, but all have the same beam. Beam is, therefore, removed as a variable and the resulting data may be investigated for the influence of other factors such as hull angles.

In summary, therefore, the following steps have been taken in order to present the powering data in the format of Figure 4.2.1, where meaningful comparisons of the overall powering and hull performance efficiency between the vessels can be made.



- Analysis concentrated on Winter ice conditions test data.
- Powering performance data interpolated at 1, 2 and 3 m/s.
- Power data corrected linearly to 19.25m beam.
- Inerta covered hulls (plus Kigoriak with bare, smooth hull).
- No icebreaking auxiliary systems operating.

The power data corrected for beam are given in Table 4.2.2 (D).

#### 4.2.3 Results

It is seen from Figure 4.2.1 that the power versus ice thickness curves at 1 m/s for the different vessels in the group have very similar shape, do not cross one another and show different absolute levels of slow speed powering performance in ice. As such, the data show a similar level of consistency as for the full power performance data.

The lowest power for a particular slow speed performance in ice is offered by Robert Lemeur and the highest by Terry Fox. Since the data have been corrected to the same beam, it may now be said that the combination of the hull form and propulsion arrangement of Robert Lemeur provides the most efficient low speed powering performance of the vessels in the group in straight level icebreaking. The Terry Fox has, likewise, the least efficient powering performance, due in part to its open propeller arrangement, which is less efficient than a ducted arrangement at low levels of propeller-ice interaction, such as is normal in ahead icebreaking in low to medium thickness of first year level ice.

As stated above, these powering data are not suitable for the comparisons intended in this study of the effect of hull form and features on icegoing performance. In order to make these comparisons, the propulsion element will be removed from the data, allowing the comparisons to be made on the basis of icegoing resistance. The powering data presented in this section are the first step in this process.

#### 4.2.4 Conclusions

The power versus ice thickness data for low speed level icebreaking show a similar level of consistency as for the full power performance data.

The most efficient low speed level icebreaking powering performance is offered by Robert Lemeur and the least efficient by Terry Fox.

In order to make the comparisons between different designs, as required to meet project objectives, the powering data must be analyzed further and presentations made on the basis of icegoing resistance.

#### 4.3 Open Water Propulsion Performance

##### **4.3.1 General**

Propulsion power is translated into resistance by multiplying by the net propulsive thrust per unit power acting on the vessel in its condition of dynamic equilibrium at a specific speed and power level. Net propulsive thrust is the thrust generated by the propulsion system - open propeller or propeller and duct combination - less the thrust deduction or interaction drag between the propulsion system and ship hull. The net propulsive thrust at a given speed and power level is, therefore, equal to the net external force on the unpowered vessel which, by definition, is vessel resistance.

At low levels of propeller-ice interaction, as occurs generally with the vessels in this group in moderate level ice thickness, the open water propulsion system characteristics are barely affected. Open water propulsion data and data obtained when propeller-ice interaction is judged to be negligible are, therefore, used as the primary means of translating power to resistance. Such full scale data for propulsion system performance are available for Kigoriak, Robert Lemeur and Terry Fox and are analyzed to determine the relationship between propulsion power and ship resistance at different speeds and power levels. Equivalent data are not available for the other vessels in the group. Consequently, each vessel in the group with ducted propellers cannot have its own power to resistance conversion data.

The approach taken, therefore, is to develop two sets of power to resistance conversion data to account for the recognized major differences in propulsion characteristics between open and ducted propulsion systems. Conversion data for the ducted vessels are based on the full scale data for Kigoriak and Robert Lemeur. Terry Fox, as the only open screw vessel, uses its own trials propulsion data.

It must be recognized that, other than the major influence of open versus ducted propellers, many other factors associated with both the particular design of the hull, especially in the stern region, and the arrangement and scale of the propulsion system, can influence the power to resistance conversion data. In general, however, these effects will be small (5 - 10 %) in relation to the influence of ducts (25 %). Even with all known model data for the vessel as well as the

full scale data, it would be a major undertaking, far beyond the scope of this project, to modify the power to resistance conversion data for each of the ducted vessels.

Derivation of the power to resistance conversion data for open and ducted propulsion systems in open water or ice free conditions is described below. The effect of propeller-ice interaction on propulsion systems is considered separately in Section 10.

#### **4.3.2 Data Analysis**

##### **Ducted Screw Propulsion Systems**

Full scale propulsion data for Kigoriak and Robert Lemeur are analyzed in order to provide power to resistance conversion data for all ducted screw vessels in the group.

The primary analysis is included in the source material where net propulsive thrust of the ducted system is estimated from the propeller designer's open water physical model data at the full scale ship speed, propeller pitch and shaft speed recorded in each test.

The net propulsive thrust for a fixed size of propeller per unit power is known to be a function of both absolute shaft power and ship speed. The analyzed full scale data from the reference sources are, therefore, plotted in this form in Figure 4.3.1 (D) for speeds of zero (bollard) to 9 m/s for the power range up to 12 MW.

The full scale bollard tests were conducted by pushing against large immovable ice floes with the hull and propulsion systems in open water. Data for forward speeds of 1 to 9 m/s were obtained from the full power performance tests in thick level ice at 1 m/s down to open water at the highest speeds. Propeller-ice interaction in these level ice tests was, at the worst, intermittent and small.

Power to resistance conversion curves for discrete speeds have been constructed from the source material. The curves pass through or very close to the high power data points for Kigoriak and the 3 to 7 m/s data points for Robert Lemeur. Only in the lower power bollard conditions is it necessary to draw a mean line through data. The maximum difference between an original data point and corresponding curve is 5%.

The data in Figure 4.3.1 (D) are tabulated in Table 4.3.1 (D), which is a generic table of conversion factors from power to resistance for all ducted vessels in the group. In the interests of clarity, the conversion curves are presented in Figure 4.3.2 without the full scale data points.

## Open Screw Propulsion Systems

The analysis is similar to that for the ducted system above except that the source data are analyzed and presented in terms of shaft thrust and not net propulsion thrust. Some 37 data points are used covering a speed range of 0 to 3.5 m/s. The data are plotted in Figure 4.3.3 (D) as thrust per unit power versus propulsive power. The bollard shaft thrust curve is drawn through the three available data points and it is observed that the effect of speed upon power is approximately 3-4% reduction per m/s increase in speed. This effect is also determined from open water propulsion model tests for M.V. Kalvik carried out at IMD.

In order to convert shaft thrust to net propulsive thrust, a thrust deduction factor of 0.09, the same as used for Kigoriak, is employed. This factor has not been separately determined for Terry Fox, but is judged to be an appropriate figure, bearing in mind the twin open propellers and clean open design of the stern.

The resulting data for net propulsive thrust per unit power versus power for speeds of 0 to 9 m/s are given in Figure 4.3.3 (D) and Table 4.3.2 (D). These data are subsequently used to convert the test power data for Terry Fox to resistance. They are presented without the full scale data points in Figure 4.3.4.

### 4.3.3 Results

By comparing the two sets of power to resistance conversion curves the following points are noted:

- net specific propulsive thrust per HP on shaft (or tow rope pull/resistance) is highest at low powers and reduces at a decreasing rate with increase in power.
- the net propulsive thrust or resistance curves for the ducted propulsion system are significantly higher at low speeds than those for the open propeller system. At a speed of 1 m/s the ducted curve is 25% higher.
- the relative difference between the curves reduces with increasing speed. At 7 m/s they are almost identical and at 9 m/s, the open screws have a slight efficiency advantage.

The impact of open or ducted screw propulsion on the installed power required for a given ship performance in conditions where propulsive thrust is not adversely affected by propeller-ice interaction, such as in most level icebreaking situations, is shown by comparing Figures 4.3.2 and 4.3.4.



An open screw vessel requiring 10 MW of power to break a given thickness of level ice at 1 m/s experiences a resistance of  $10 \times 0.116 = 1.16$  MN. This same resistance may be overcome by fitting a ducted screw operating at 7.5 MW of power -  $7.5 \times 0.155 = 1.16$  MN - a 25% reduction in power. Alternatively, the open screw vessel requires 33% more power for the same performance.

The major performance advantage of the ducted propulsion system is, therefore, noted. In different situations such as at higher speeds and where propeller-ice interaction is significant, the relative advantages of the alternate systems can change.

#### 4.3.4 Conclusions

Conversion data for translating propulsion power into net propulsive thrust or ship resistance have been derived for open and ducted propulsion systems.

The data for the open propellers apply specifically to Terry Fox and those for the ducted propellers apply to Kigoriak and Robert Lemeur with little compromise. The remaining vessels, Ikaluk, Arctic Ivik and Max Waldeck have ducted propulsion systems for which no open water propulsion system analysis data exist. The conversion data for Kigoriak and Robert Lemeur will, therefore, be applied to those vessels in the derivations of ship resistance.

### 4.4 Resistance Versus Ice Thickness at Constant Speed, Winter

#### 4.4.1 General

Resistance versus ice thickness data for level icebreaking are calculated and presented in Table 4.4.1 (D) and Figures 4.4.1-3 for ship speeds of 1, 2 and 3 m/s.

Figures 4.4.1-3 show the true relative resistances of the hull forms in level Winter ice conditions and may, therefore, be used to determine parametric influences upon level ice resistance.

It must be remembered that these data do not show the true relative resistances of the individual ships themselves since all data are corrected or normalized to the same beam. Therefore, for example, although Terry Fox has a normalized resistance at 1 m/s in 0.9m level ice which is  $(0.735/0.6 - 1)$  22% greater than Kigoriak's, the actual ship Terry Fox has a resistance which is  $((0.735 \times 17.5/19.25)/0.6 - 1)$  11% higher than Kigoriak.



As discussed in Section 4.2, the resistance data at 1 m/s provide the most suitable indication of the icebreaking component of level ice resistance, while the resistance increase from 1 to 3 m/s incorporates predominantly the ice clearing component.

The effect of environmental and hull form parameters upon level icegoing resistance is investigated and discussed below.

#### 4.4.2 Analysis

The power versus ice thickness data in Table 4.2.1 (D) are translated into resistance versus ice thickness data using the conversion data for the appropriate propulsion system, speed and power in Tables 4.3.1 (D) and 4.3.2 (D). The resulting resistance data for the vessels in the group are given in Table 4.4.1 (D) and plotted in Figures 4.4.1-3 for ship speeds of 1, 2 and 3 m/s respectively.

As stated in Section 4.3.1, the power to resistance conversion data were obtained on the basis of minimal propeller-ice interaction in the propulsion data analyzed for Kigoriak, Robert Lemeur and Terry Fox/Kalvik. Similarly, the level ice resistance data calculated for the vessels are only free of propeller-ice interaction effects if the level ice tests from which they are derived were free of propeller-ice interaction. The only recorded case where propeller-ice interaction was prevalent was during the trials of Arctic Ivik when ice entered the propulsion system in level ice at an average 4 times per minute. This caused pitch reduction from level 5 to 3.5 in 5 seconds, with recovery in 5 seconds. This has been calculated to give a net average thrust reduction of 7%. Consequently, the resistance in Table 4.4.1 (D) has been reduced by 7% prior to plotting.

The resistance comparisons in Figures 4.4.1-3 are, therefore, made on the following basis:

- Winter ice conditions.
- Inerta covered hulls (plus Kigoriak with bare smooth hull).
- No hull lubrication system operating.
- Data corrected to same beam (19.25m).
- Ice-free propulsion.
- Same specific powering performance for all ducted vessels.

In order to investigate parametric influences further than those shown in Figures 4.4.1-3, additional presentations are made.

The resistance data for 1, 2 and 3 m/s are normalized in Table 4.4.2 (D) relative to Kigoriak (Inerta) data at 100 %,

and the relative resistances in different thicknesses of ice plotted in Figures 4.4.4-9 against average buttock angles and average flare angles across the bow at the icebreaking waterline.

Additionally, the increases in resistance from 1 to 3 m/s are given in Table 4.4.3 (D) and are plotted against ice thickness in Figure 4.4.10.

Furthermore, in order to show the efficiency of vessel design for level icebreaking relative to size or displacement, the resistances of the vessels, uncorrected for beam, are divided by displacement and given in Table 4.4.4 (D) and Figures 4.4.11 and 12.

#### 4.4.3 Results

##### Resistance Versus Ice Thickness, Figures 4.4.1 to 3

These data show the true relative resistances of the hull forms in level Winter ice conditions. At all speeds, it is noted that the resistance curves for the vessels have very similar shape, although absolute levels of resistance are different. This degree of consistency in the data has been evident in the full power performance and power versus ice thickness data presented previously. The major difference in the resistance data compared with the power based performance data is the relative position of the Terry Fox results. When account is taken of the lower efficiency of open screw as opposed to ducted screw propulsion, the Terry Fox hull form resistance curve is shown to be lower relative to all vessels in the group. The results also show the marked reduction in icegoing resistance of approximately 25% due to low friction Inerta coating instead of smooth bare steel on Kigoriak.

At 1 m/s, Figure 4.4.1, the lowest resistance curve is that for Robert Lemeur followed by Kigoriak, Terry Fox and Ikaluk. Only individual data points are available for Arctic Ivik, which is very close to Kigoriak in this ice and for Max Waldeck which lies between Robert Lemeur and Kigoriak.

At this low speed, the icebreaking component of level ice resistance predominates. The rate of increase of resistance with increase in ice thickness is an important performance prediction factor normally expressed as  $(\text{ice thickness})^x$ , when  $x$  is the thickness exponent. For ice thicknesses between 0.75m and 1.0m, the four resistance curves show very similar thickness exponents with an average of 1.45. This means that doubling ice thickness increases resistance by 173 %.

At 2 m/s, Figure 4.4.2, the average thickness exponent has lowered to 1.27, demonstrating how the ice clearing compo-

nent of resistance is becoming relatively more important and has a lesser dependency on ice thickness than the icebreaking component.

The most noticeable difference between the results for 1 and 2 m/s is the large increase in resistance for Robert Lemeur relative to the other vessels. Robert Lemeur has still the lowest resistance, but is now very close to Kigoriak.

At 3 m/s, Figure 4.4.3, the resistance of the Robert Lemeur hull form has again taken a larger increase than the other forms. Kigoriak now has the lowest resistance with Robert Lemeur slightly higher, followed by Terry Fox and Ikaluk.

The average thickness exponent is yet lower at 1.11.

#### **Resistance Versus Bow Angles, Figures 4.4.4-9**

The results show a very clear trend of reducing hull form level icegoing resistance with the decrease of buttock angle. The influence of flare angle is equally clear with icegoing resistance decreasing as average flare angle increases from about 40 to 70°. Thereupon the influence reverses slightly for flare angles above 70°. The rate of change of icegoing resistance is greatest at larger buttock angles and low flare angles.

The data do not form unique curves and this is to be expected. If they did, it would demonstrate a singular parametric influence upon icegoing resistance which is not expected. The data do, however, show that average buttock and flare angles have a major influence upon icegoing resistance.

The absolute level of change in ice resistance with both angles is however considerably higher than might be expected. This matter is discussed in detail in Section 11, Performance Estimation Models. The possible reasons are two fold. Firstly the data have not been corrected exhaustively for differences in environmental conditions and propulsive performance and secondly there are several other hull parameters and features which can influence ice resistance but are not identifiable in the full scale data analysis.

#### **Resistance Increase from 1 to 3 m/s, Figure 4.4.10**

The velocity component of icegoing resistance is presented and shows very graphically the trends noted in Figures 4.4.1-3. The Robert Lemeur hull form has a low velocity component of resistance in thin 0.6m ice, but this increases rapidly relative to the other vessels as ice thickness increases. In 0.9m of ice at 3 m/s, the velocity component of resistance is 24% higher than Ikaluk and 46% higher than for Kigoriak.

The rate of increase in the velocity component with increase in ice thickness is relatively similar for Kigoriak, Terry Fox and Ikaluk. The absolute levels of the velocity component are lowest for Kigoriak, slightly higher for Terry Fox, and yet a little higher for Ikaluk. This could be explained by the added velocity resistance due to the wedges under the bows of Terry Fox and Ikaluk.

It is considered that the velocity component of resistance for Robert Lemeur in thick ice is somewhat exaggerated and may be partly due to influences which cannot be judged from the available information. High interaction forces between heavy ice and hull appendages and lower propulsive efficiency than anticipated are possible causes. More information and in depth analysis would be required in order to resolve this matter.

#### **Resistance Per Tonne Displacement, Figures 4.4.11 and 12**

The effect of ship size or displacement on efficiency of design for level icebreaking is shown in Figures 4.4.11 and 12. It is seen that at 1 m/s, the lowest resistance per tonne is obtained by Robert Lemeur despite her being smaller than both Kigoriak and Terry Fox. This advantage is lost to Kigoriak at 2 m/s and also to Terry Fox at 3 m/s.

Terry Fox and Kigoriak are very similar in size and it is seen that Kigoriak maintains a slight advantage of about 10% in terms of level icebreaking resistance per tonne displacement over the speed range 1-3 m/s.

The remaining vessels in the group show the expected relative results, with the smaller vessels showing progressively lower efficiencies on this basis of comparison as displacement reduces.

Robert Lemeur has got a large displacement due to its very high block coefficient of 0.7. This is unique for icebreakers which normally have a block coefficient less than 0.6.

#### **4.4.4 Conclusions**

Valuable benchmark data of reliable origin and in a common format have been produced for ahead level icegoing resistance in Winter conditions. The data demonstrate a clear trend of reduction in hull form icebreaking resistance with decrease in average buttock angle and increase in average bow flare angle, upto about 70°. Thereupon the influence of flare angle reverses. The rate of change of resistance is greatest at larger buttock angles and lower flare angles. The level ice



thickness exponent for slow speed icebreaking for the group of hull forms is a low figure of 1.45.

With increase in speed, ice clearing resistance becomes increasingly significant and the ice thickness exponent correspondingly reduces. It is judged that consequently the level ice resistance data are influenced significantly by additional parameters which can not be isolated in this analysis. The analysis could need to cover a wider range of icebreaking vessels in order for the additional influences to be determined.

The absolute level of change in ice resistance attributed to bow angles is higher than might be expected. These changes are to a large extent real between the ships evaluated and can not be explained by limitations in the data analysis.

The icegoing resistance per tonne displacement for vessels in the group generally increases with decrease in displacement. The exception is Robert Lemeur at low speed. Despite having the third largest displacement, her low speed icebreaking is so efficient as to result in the lowest resistance per tonne.

Robert Lemeur demonstrates how a low ice resistance can be achieved by a high block coefficient vessel through the short bow with reasonably shallow buttock angles.

#### 4.5 Influence of Hull Lubrication Systems

##### 4.5.1 General

The effect of three different hull lubrication systems upon level ice power requirements are presented.

- Low pressure hull water wash system on Kigoriak, involving the gravity dump of water 1 m above the waterline in front of the bow to the reamer chine.
- High pressure air bubbler system on Terry Fox. Air is ejected at high pressure along the bilge region of the vessel, on frames 5 to 2.
- High pressure underwater jets on Ikaluk. Water with passive air induction is ejected below the waterline at side, from stem to first chine.

The hull lubrication systems influence level ice powering through friction reduction, due primarily to lubrication of contact between ice and the hull and also in the case of high pressure water jets, lowered pressure of ice on the hull.



Other vessels in the group with the above or different systems are as follows:

Robert Lemeur - low pressure hull wash; air bubbler system  
- high pressure underwater water jets.

Max Waldeck - high pressure underwater water jets.

In the latter cases, however, there are no available systematic full scale data on which to base an analysis.

All available data on the three hull lubrication systems are analyzed and presented below.

#### 4.5.2 Data Analysis

Full scale tests for Kigoriak, Terry Fox and Ikaluk have been carried out both with and without the lubrication systems operating in a range of ice thicknesses in both winter and Spring ice conditions. In every case, tests with and without a system operating were carried out at the same time and in the same ice. Comparisons may, therefore, be drawn directly from the data without the need of corrections for ice properties.

The data are analyzed and presented in terms of the system efficiency ratio.

- Shaft power reduction effected by operation of the system
- power required to operate the system.

Consequently, when this ratio is greater than 1, there is a net power saving in operating the system and vice-versa.

The powering data and source references are given in Table 4.5.1 (D). Differences in power required for the vessels to traverse level ice at a specific speed due to operation of the lubrication system are calculated and divided by the system power. All data are then plotted in Figure 4.5.1, which gives system efficiency ratio versus level ice thickness for different ship speeds in Winter and Spring ice.

#### 4.5.3 Results

Figure 4.5.1 shows that the water wash system on Kigoriak is clearly superior in reducing level icegoing power requirements to the air bubbler and underwater jet systems on Terry Fox and Ikaluk.

The full curves for Kigoriak are for the bare steel hull in Winter ice conditions. A clear relationship is shown of increasing system efficiency both with increasing ice thickness and with ship speed. The system efficiency ratio is always greater than 1 and rises to as high as 8.6 at 1 m/s in 1.44m of ice. The Kigoriak's water wash system has a power of 373 kW. The saving on shaft power for the same level icegoing performance is, therefore  $373 \times 8.5 = 3.2$  MW.

The water wash system is also very efficient when the hull has an Inerta coating, there being only a minor reduction in the shaft power saving relative to the bare steel results.

One result is shown for Spring ice conditions in 1.3m of ice. This shows a system efficiency ratio some 60% of that for Winter conditions. It is judged that the natural lubrication of warmer Spring ice and snow leaves less scope for improvement than with cold, dry Winter ice.

The air bubbler system, as on the Terry Fox, is seen to be at its most efficient at low speed in thick ice. This result is supported by the ships masters replies to the Questionnaire (Section 3. ). The highest efficiency noted is in thick Spring/Fall ice and it is possible that, as with the water wash system, performance may be improved in Winter ice. However, the system efficiency ratio is generally very low, being less than 1.0 in all but one case. This means that only at slow speed in thick ice does the air bubbler system, as fitted to Terry Fox, result in more shaft power reduction than the power required to run the system. Even then, the powering advantage is very small.

The high pressure underwater water and air jets on Ikaluk show the lowest performance of the three systems. The data show that the system does not reduce ship power by as much as the system requires for operation. This fact is, again, supported by the master's interviews and the system on Ikaluk is no longer used.

In practical terms, any powering advantage gained with the systems must be balanced against the installation and maintenance costs. The break even point will, therefore, in practice, be greater than 1.0. This would point to both the air bubbler and water jet systems probably not being cost effective for level icegoing. The water wash system, however, has such high values of efficiency ratio that is it almost inevitably very cost effective.

It should be borne in mind that the above comparisons are based on performance in reducing shaft power requirements in level ice conditions. The relative performance of the systems in other modes of ice operation such as ridge extraction, broken and pressured ice and channels can not be analyzed since

such tests have not been carried out. Moreover, these systems may be used for nonicegoing purposes - for example, the air bubbler system can be used as a bow thruster and for cushioning effect during docking or going alongside another vessel. Depending upon the mission profile of a vessel, these many other considerations could clearly have an impact upon the selection of a system. Operator comments related to these systems are given in Section 3.

#### **4.5.4 Conclusions**

The low pressure hull wash system on Kigoriak is clearly superior to the air bubbler and underwater jet systems on Terry Fox and Ikaluk in reducing level icegoing shaft power requirements. Shaft power has been reduced by more than eight times the hull wash system power, making the system most effective and probably the only cost effective system in the group from the point of view of level icegoing.

With the hull wash system, performance improves with increase in both ice thickness and ship speed. Hull condition is not a significant factor, but performance drops in warm Spring ice relative to cold Winter ice.

### **4.6. Influence of Hull Condition and Season**

#### **4.6.1 General**

The influence of hull condition and season upon level icegoing performance has been observed separately in Section 4.1 and 4.4. The Kigoriak data used in the previous analyses is now brought together to show the influence of hull condition and season in a summarizing graphical way. The history of the Kigoriak's level ice resistance is followed from the first level ice tests in the winter of 1980 to the latest tests in the winter of 1982.

#### **4.6.2 Data Analysis**

No additional data analysis is required, resistance data being drawn from earlier sections of this report. Hull conditions are listed in Table 2.3.

#### **4.6.3. Results**

Figure 4.6.1 provides a history of Kigoriak's level ice resistance from the first level ice tests in 1980 to the latest in 1982.

Kigoriak was delivered in the fall of 1979 with no hull coating. In the Winter 1980 (January - March) tests were performed where the hull condition was smooth bare steel. A few months later in the Spring of 1980 (June) her hull had suffered some deterioration but is here still quoted as smooth bare steel. Resistance in Spring ice was now 40 % less than in the same thickness in Winter ice. Over the following two years, the bare steel surface of Kigoriak's hull deteriorated badly through corrosion and results of the tests in the spring of 1982 show that the level ice resistance increased by 40 %. In the Summer 1982 the hull of Kigoriak was fully coated with Inerta and tests were again carried out in the Winter (November - December) 1982. Resistance was 25 % lower than with the original bare steel hull.

#### 4.6.4 Conclusions

The following influences of the hull condition and season on level ice resistance can therefore be determined from the Kigoriak:

1. Resistance in Spring/Fall level ice condition is about 60 % of that in Winter ice of the same thickness.
2. Resistance of badly deteriorated steel hull is 40 % higher than that of smooth steel hull.
3. Resistance of smooth steel hull is 33 % higher than that of Inerta coated hull.

These conclusions, even though based on the Kigoriak are representative of the physical phenomena governing the resistance. The exact percentages may be influenced by the particular hull design but the fact remains that these are major influences on the icebreaking resistance.

FIGURE 4.1.1  
 FULL POWER PERFORMANCE IN LEVEL ICE  
 Winter Conditions With Snow  
 No Hull Lubrication  
 No Correction For Beam or Power

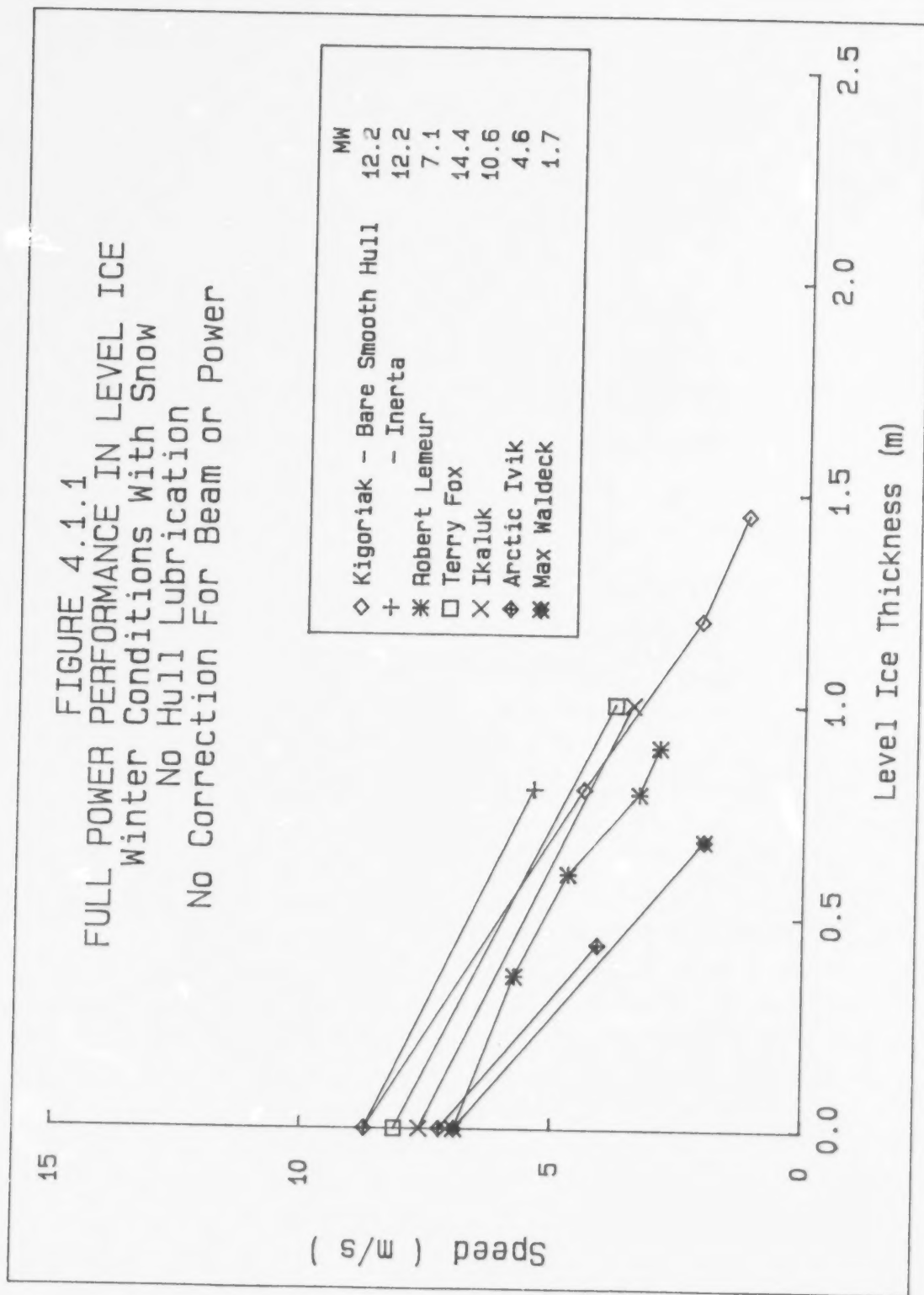
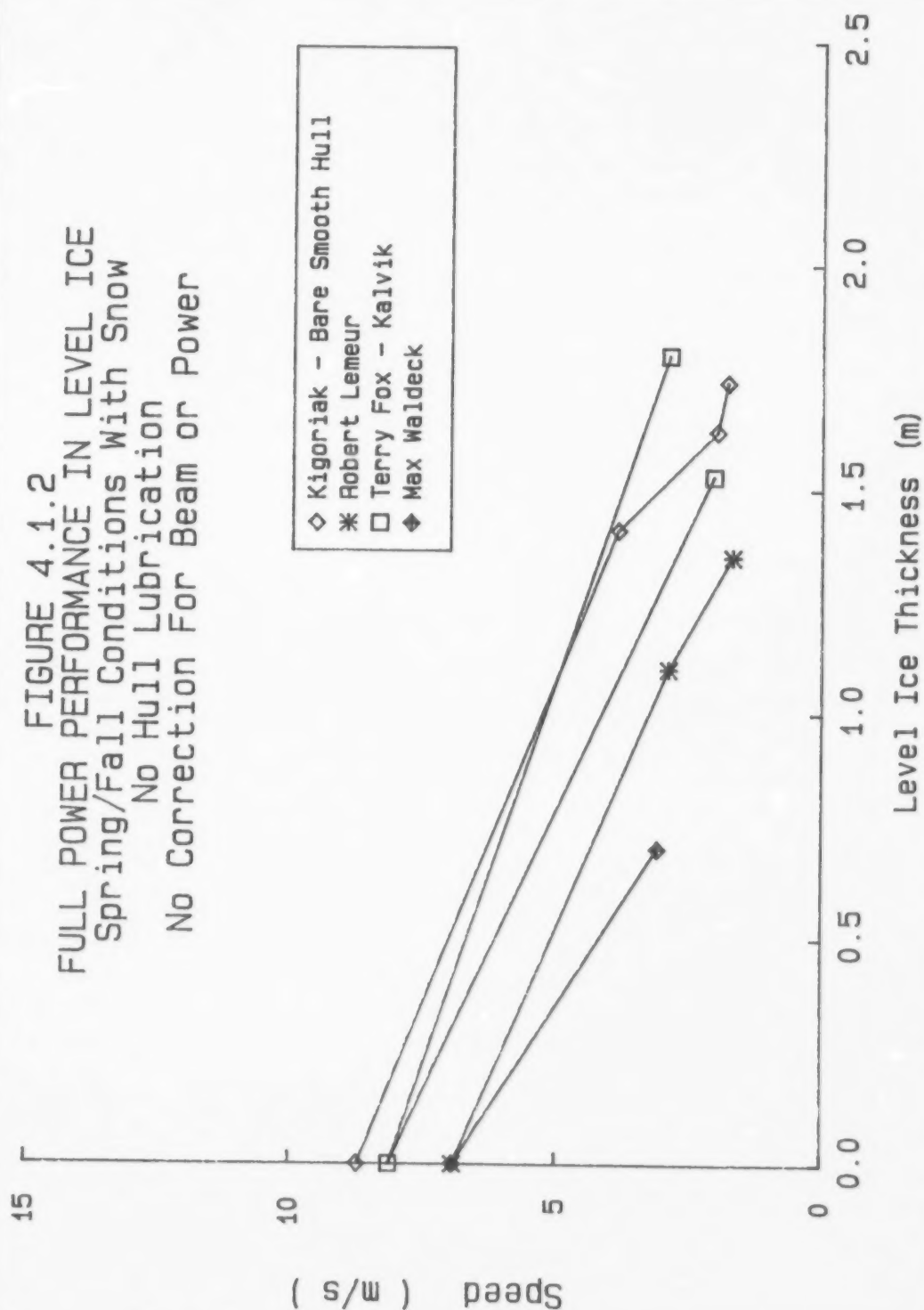




FIGURE 4.1.2  
 FULL POWER PERFORMANCE IN LEVEL ICE  
 Spring/Fall Conditions With Snow  
 No Hull Lubrication  
 No Correction For Beam Or Power



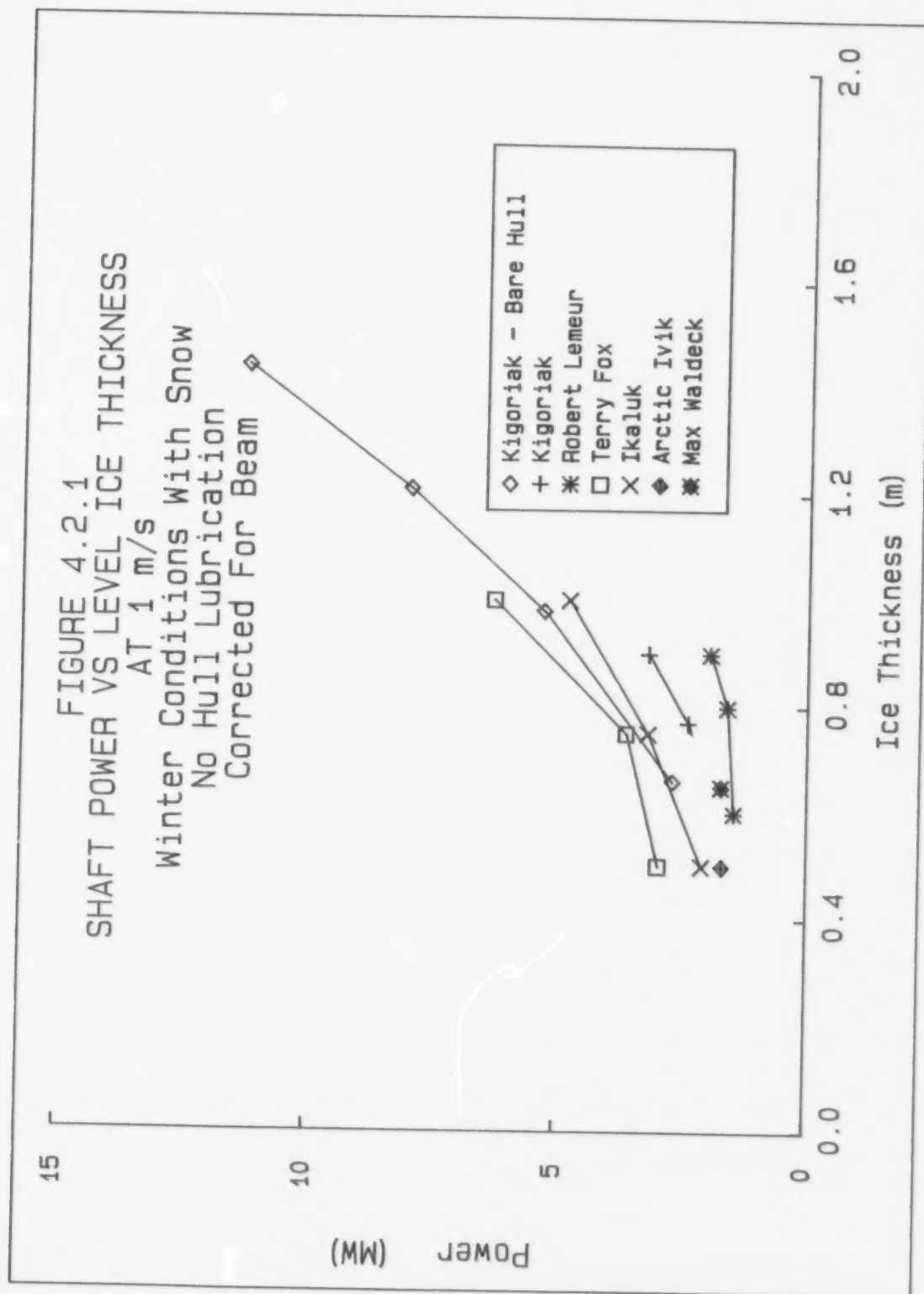


FIGURE 4.3.2  
NET THRUST PER UNIT POWER  
Ducted Propellers  
Speed: 0, 1, 3, 5, 7, 9 m/s

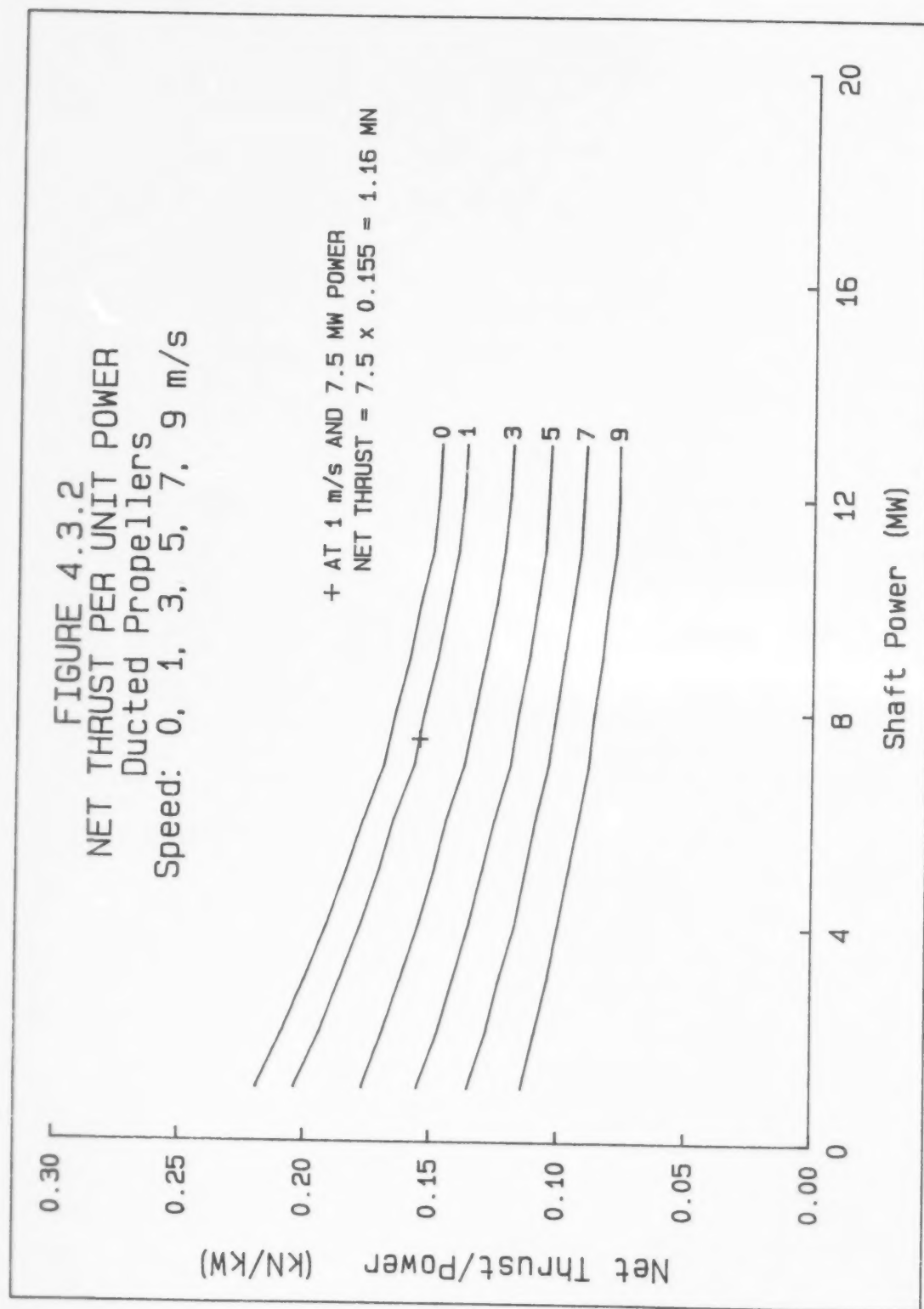


FIGURE 4.3.4  
NET THRUST PER UNIT POWER  
Open Propellers  
Speed: 1, 3, 5, 7, 9 m/s

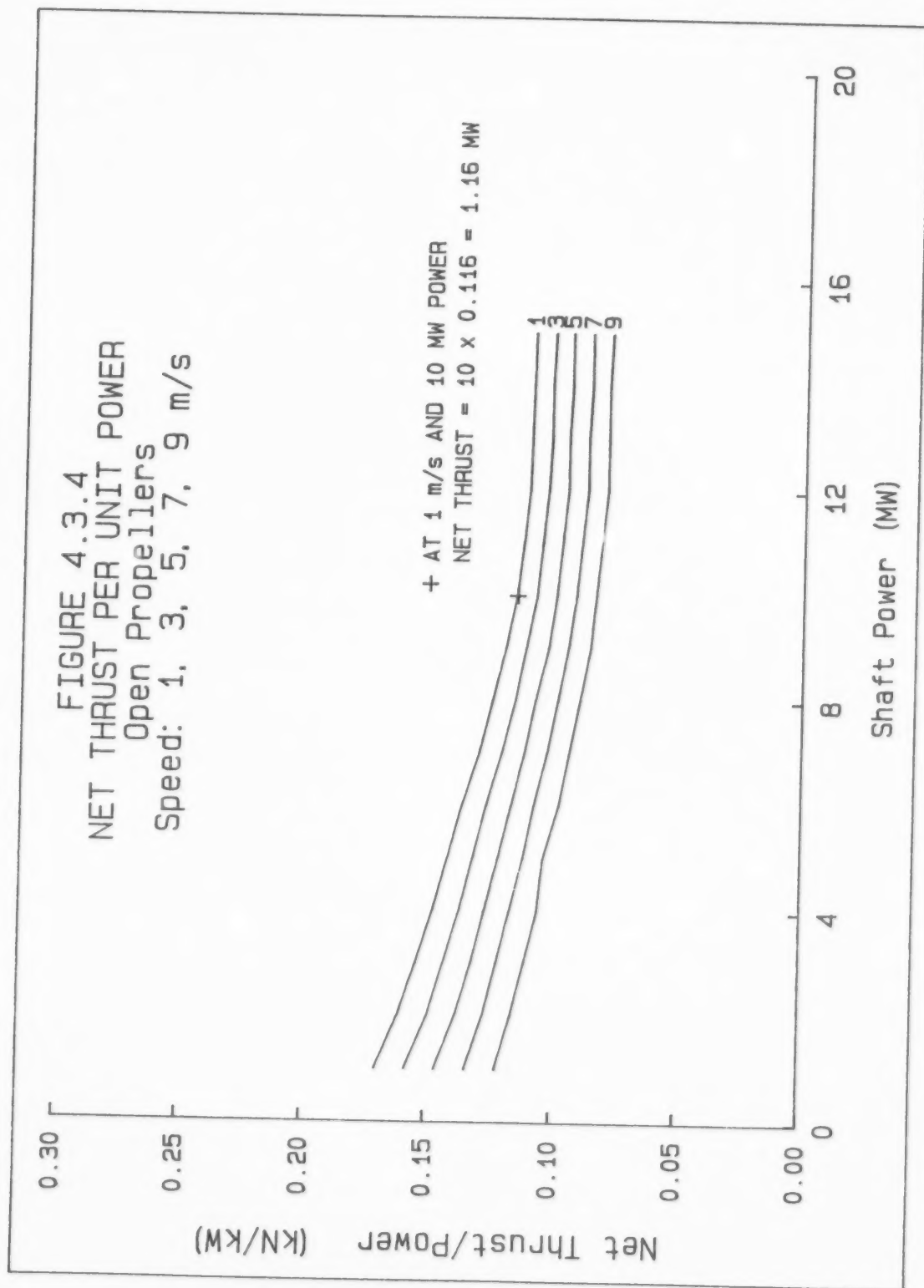


FIGURE 4.4.1  
LEVEL ICE RESISTANCE - 1 m/s  
Winter Conditions With Snow  
No Hull Lubrication  
Corrected For Beam

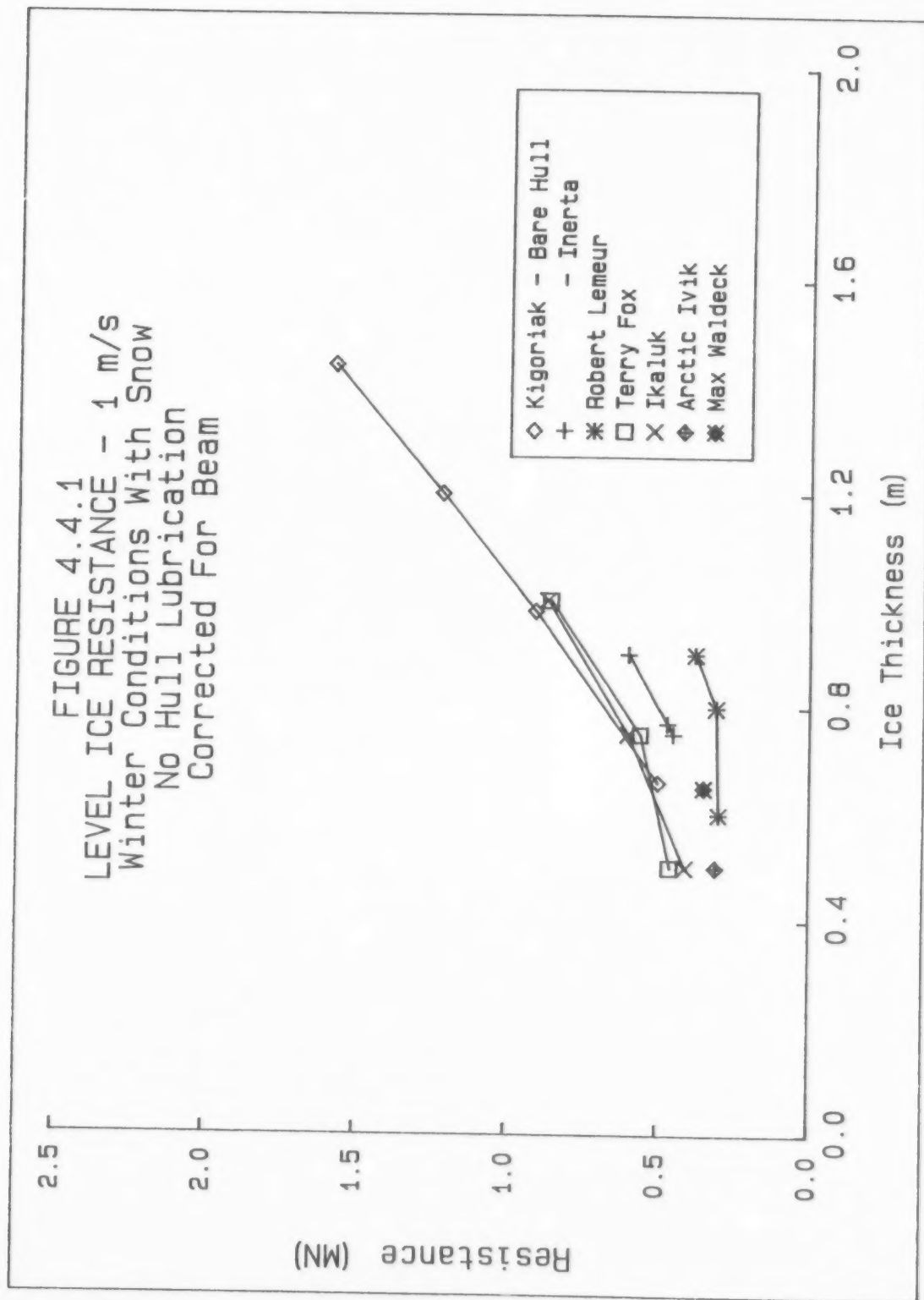




FIGURE 4.4.2  
LEVEL ICE RESISTANCE - 2 m/s  
Winter Conditions With Snow  
No Hull Lubrication  
Corrected For Beam

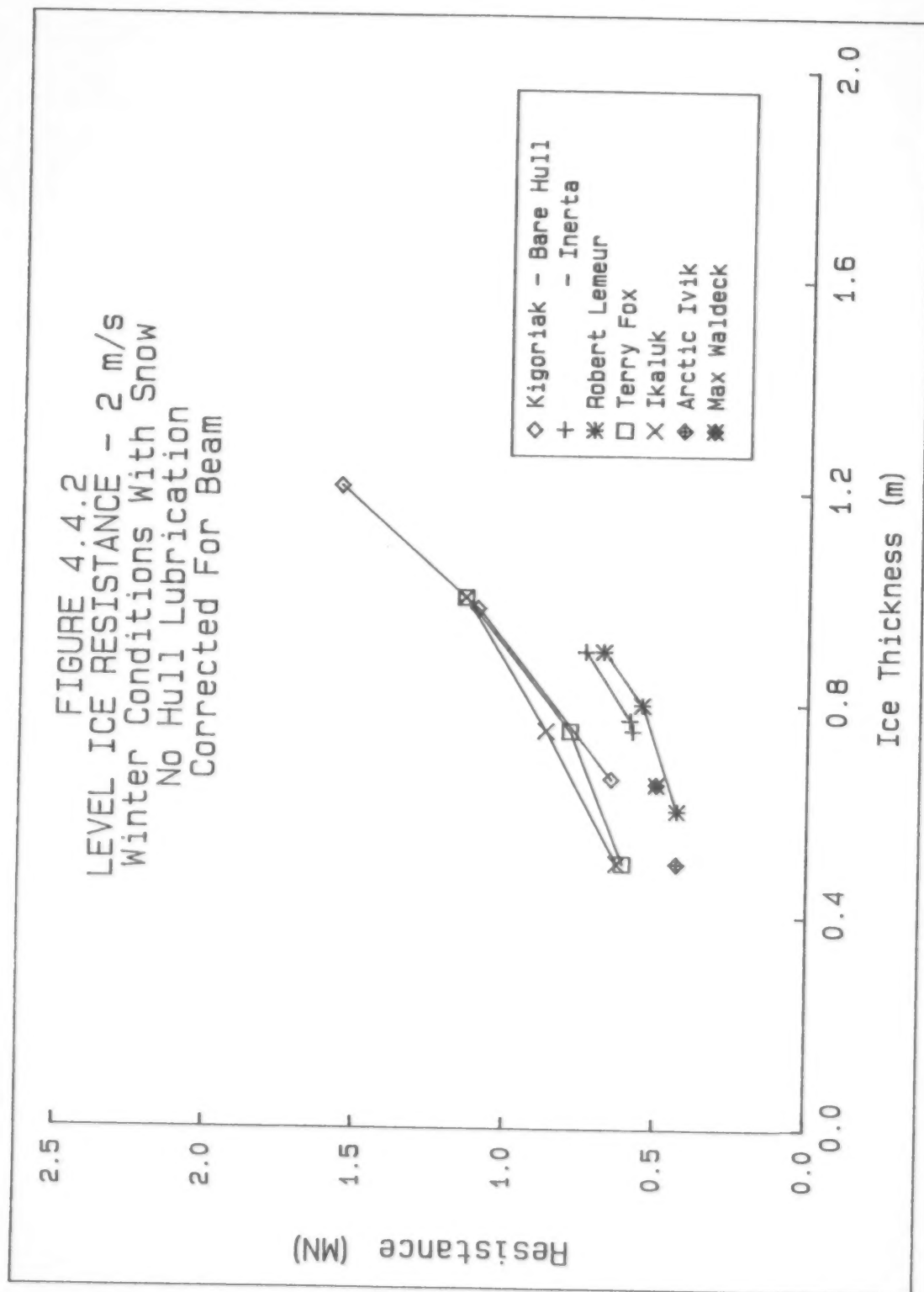


FIGURE 4.4.3  
 LEVEL ICE RESISTANCE - 3 m/s  
 Winter Conditions With Snow  
 No Hull Lubrication  
 Corrected For Beam

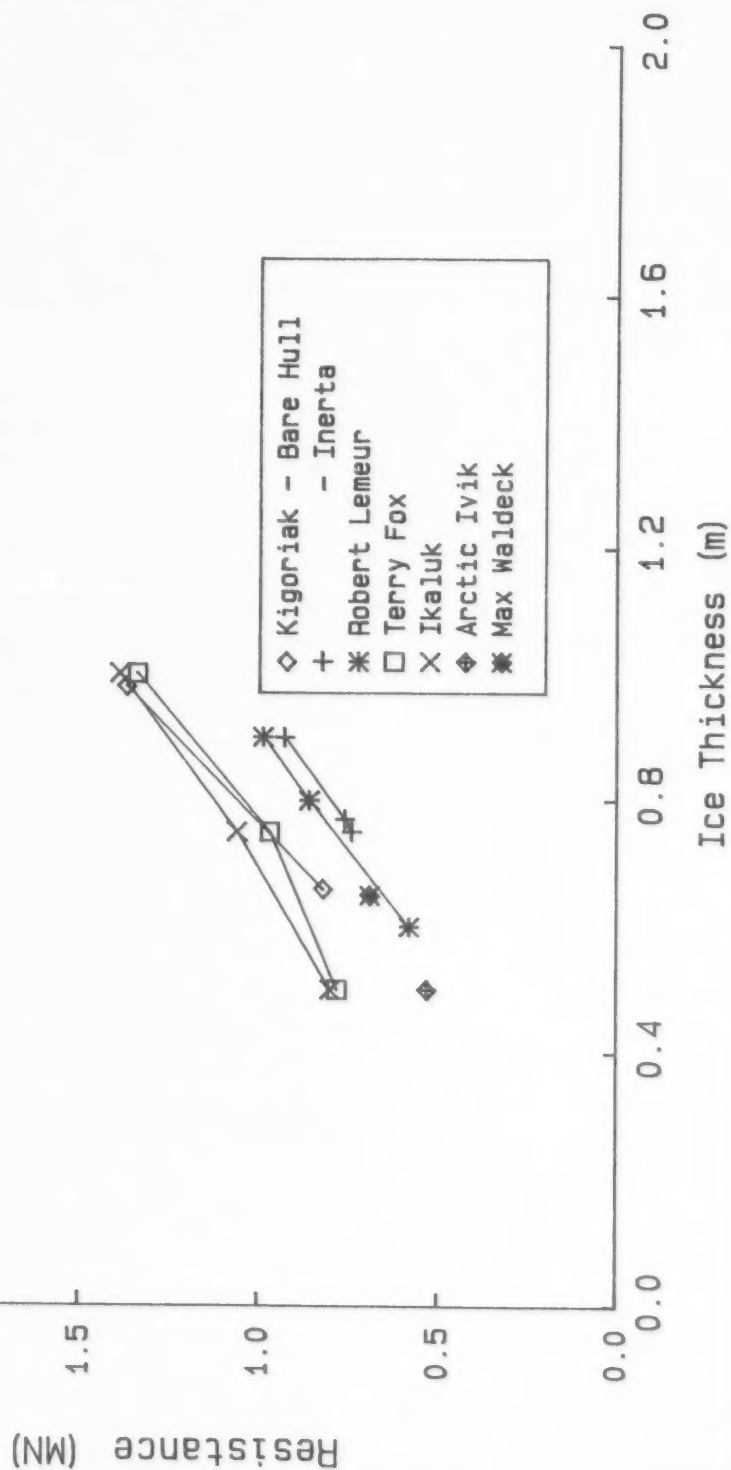


FIGURE 4.4.4  
 RELATIVE RES. AT 1 m/s IN LEVEL ICE  
 Influence of Buttock Angle  
 Ice Thickness 0.5, 0.75, 0.9 m.  
 Winter Conditions With Snow  
 No Hull Lubrication  
 Corrected For Beam

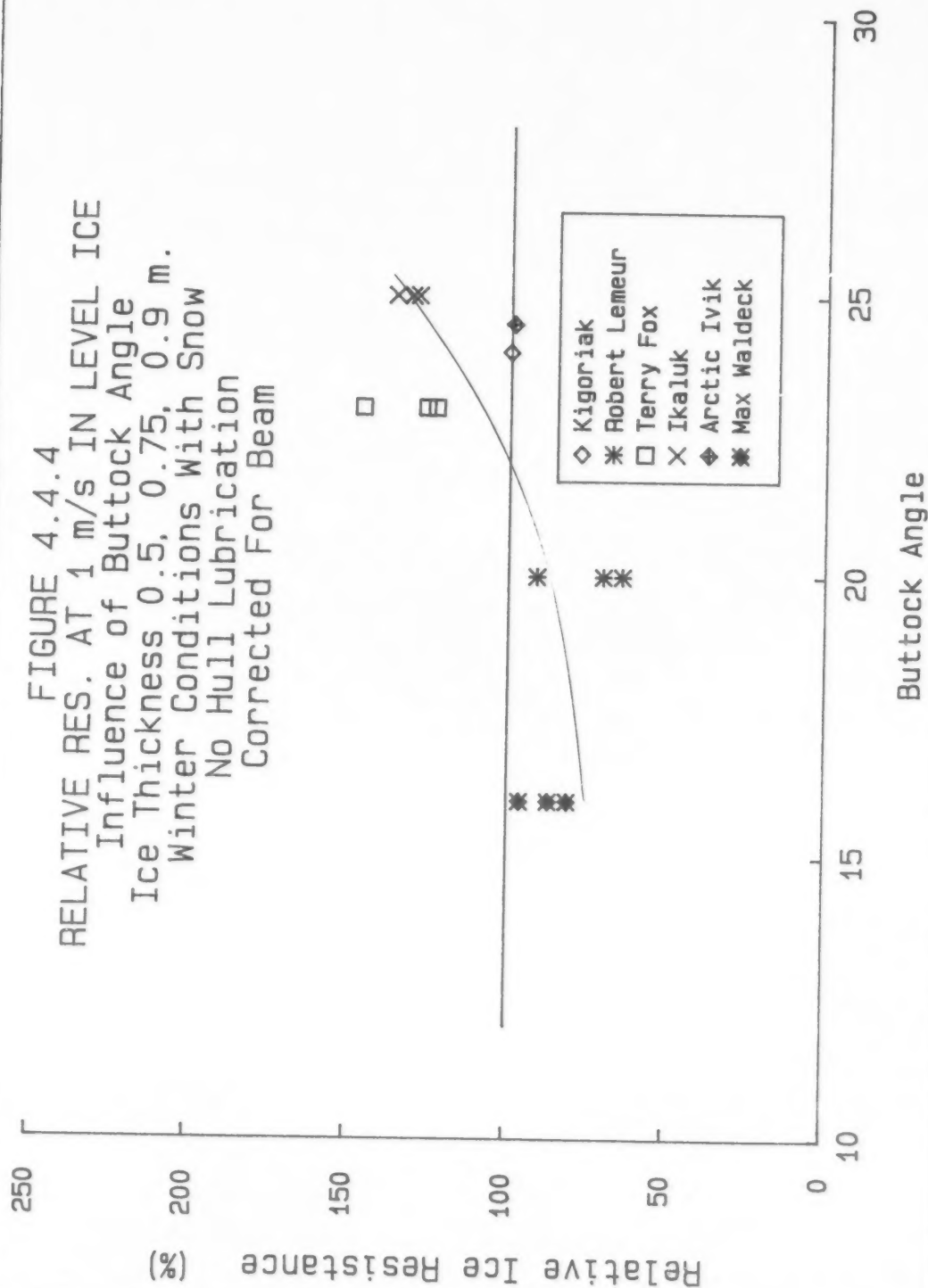


FIGURE 4.4.5  
 RELATIVE RES. AT 1 m/s IN LEVEL ICE  
 Influence of Flare Angle  
 Ice Thickness 0.5, 0.75, 0.9 m.  
 Winter Conditions With Snow  
 No Hull Lubrication  
 Corrected For Beam

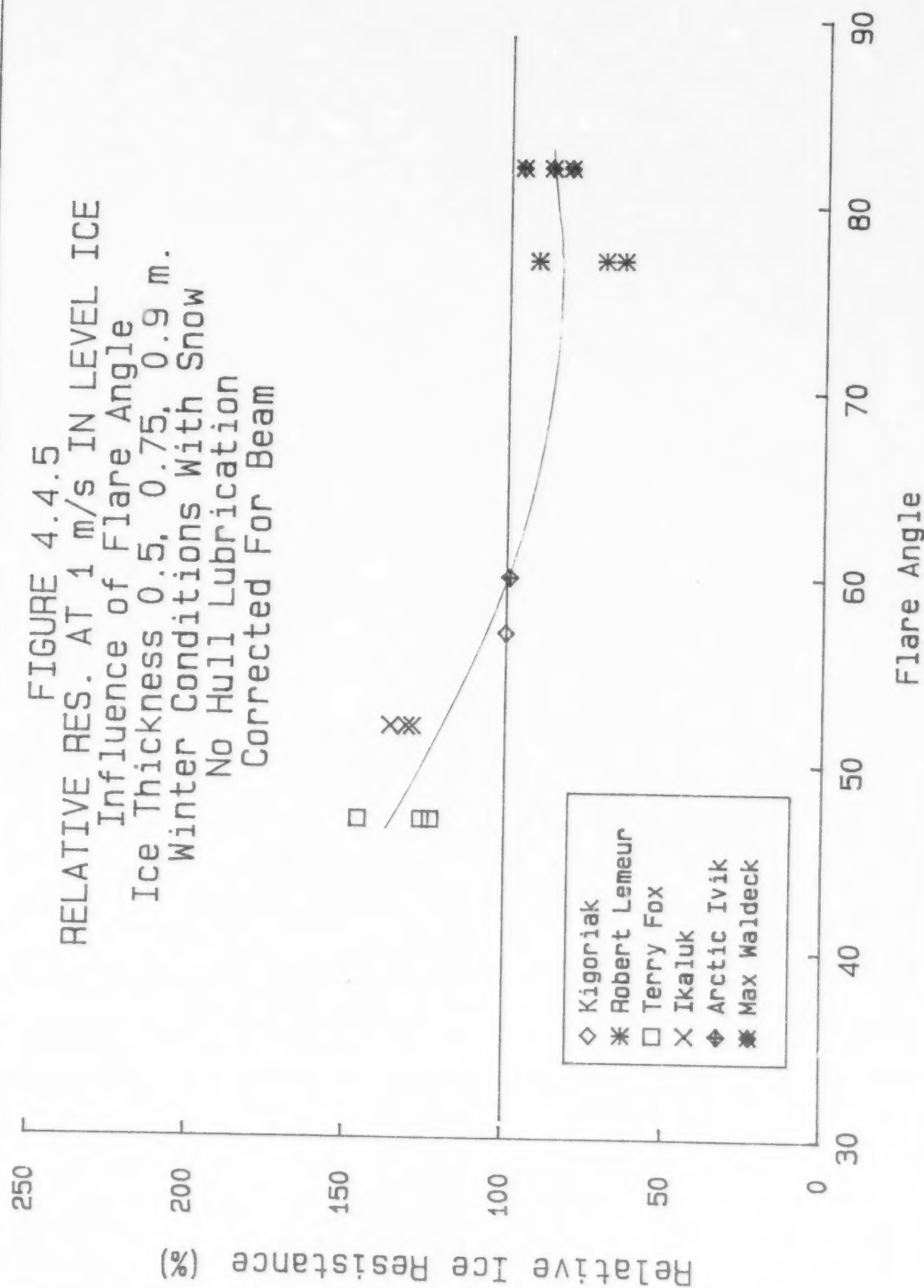


FIGURE 4.4.6  
 RELATIVE RES. AT 2 m/s IN LEVEL ICE  
 Influence of Buttock Angle  
 Ice Thickness 0.5, 0.75, 0.9 m.  
 Winter Conditions With Snow  
 No Hull Lubrication  
 Corrected For Beam

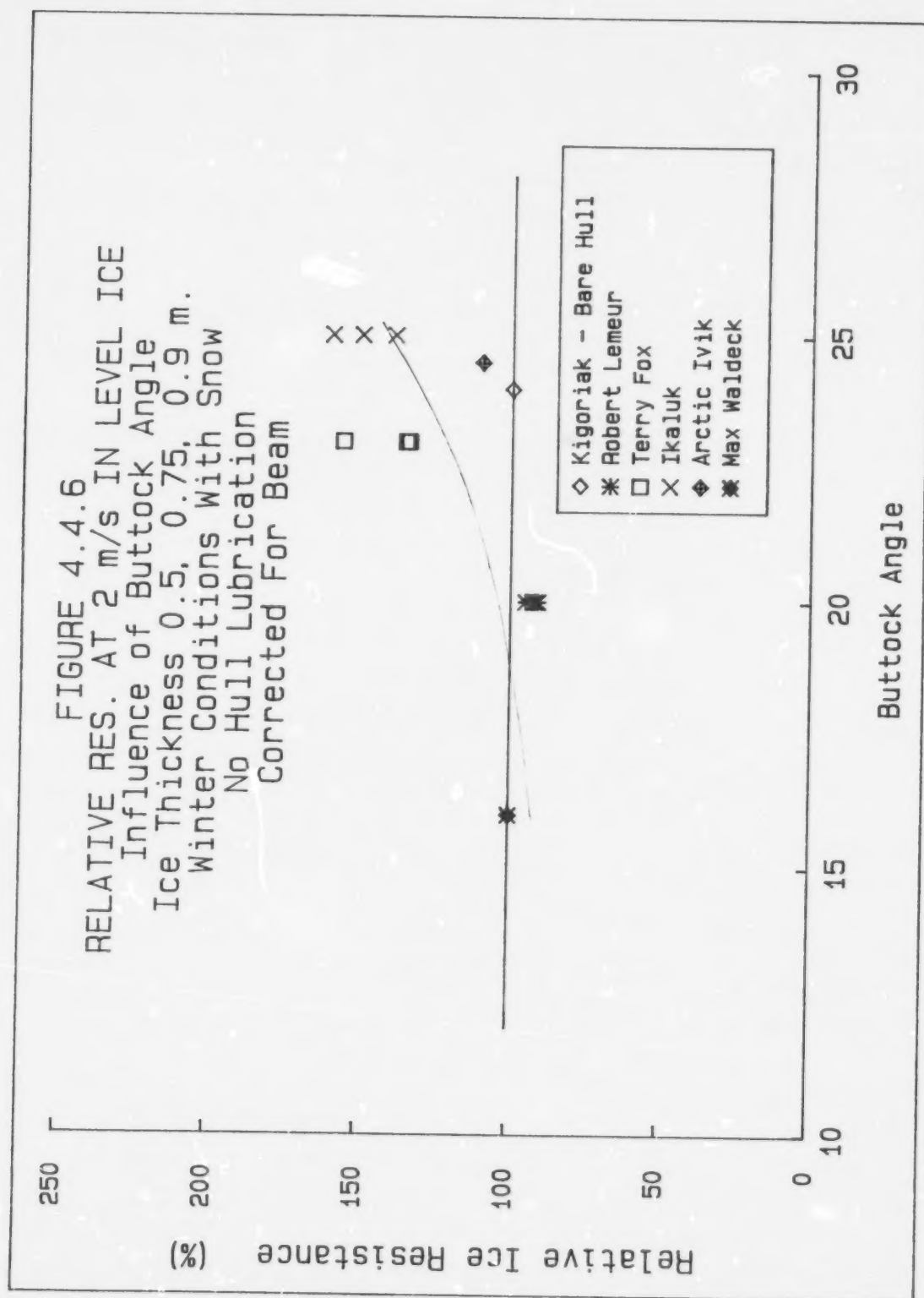




FIGURE 4.4.7  
 RELATIVE RES. AT 2 m/s IN LEVEL ICE  
 Influence of Flare Angle  
 Ice Thickness 0.5, 0.75, 0.9 m.  
 Winter Conditions With Snow  
 No Hull Lubrication  
 Corrected For Beam

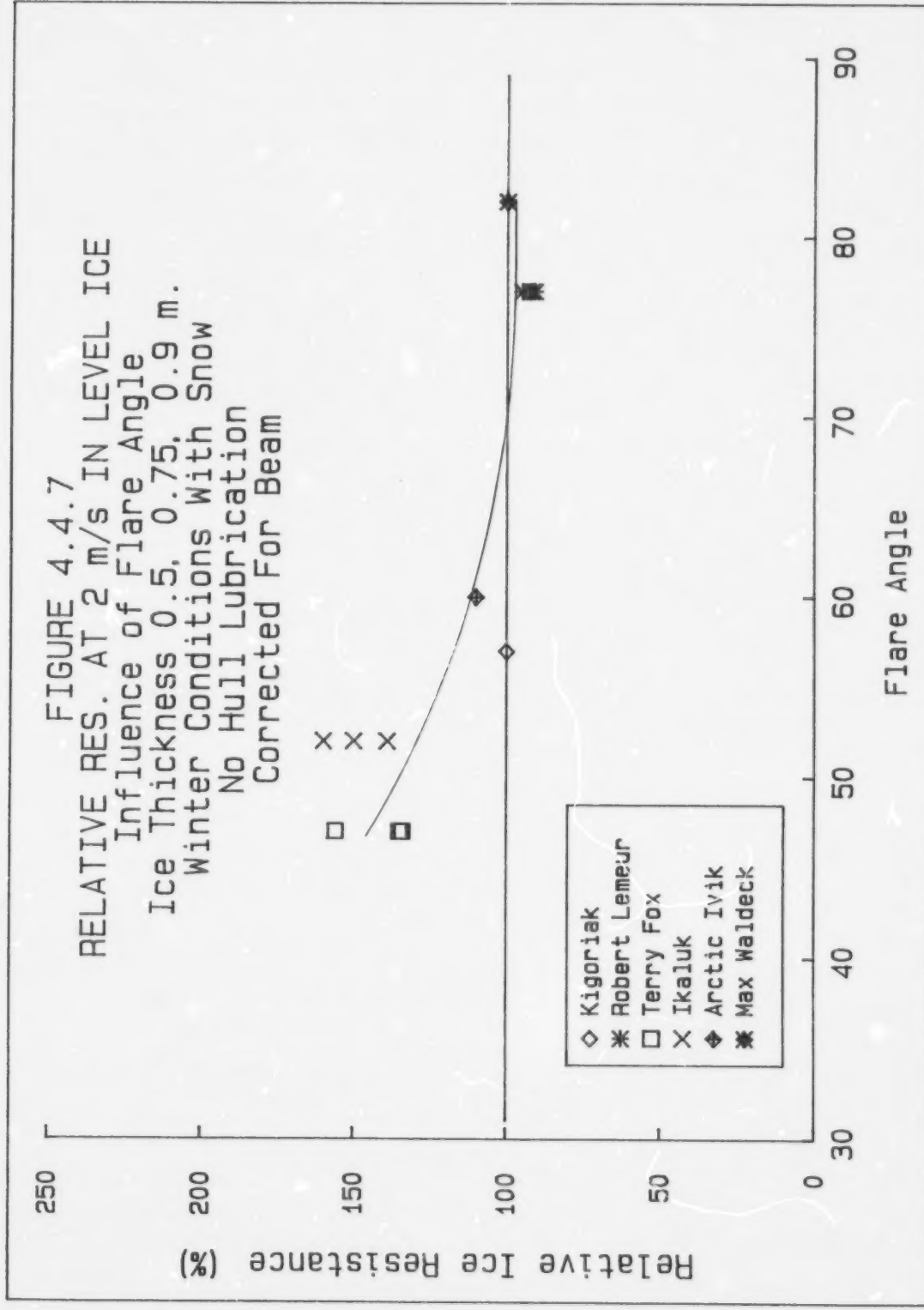
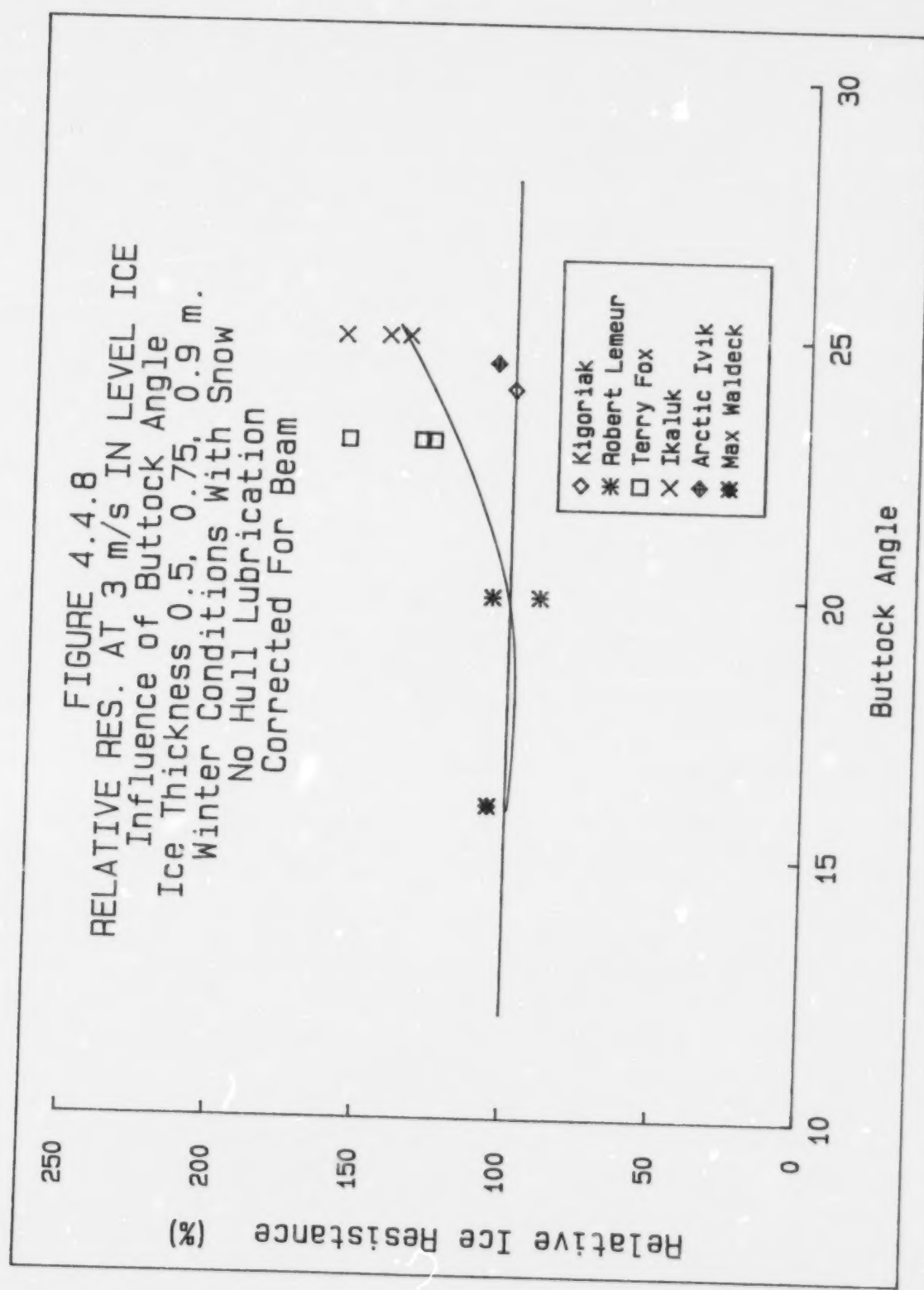


FIGURE 4.4.8  
 RELATIVE RES. AT 3 m/s IN LEVEL ICE  
 Influence of Buttock Angle  
 Ice Thickness 0.5, 0.75, 0.9 m.  
 Winter Conditions With Snow  
 No Hull Lubrication  
 Corrected For Beam



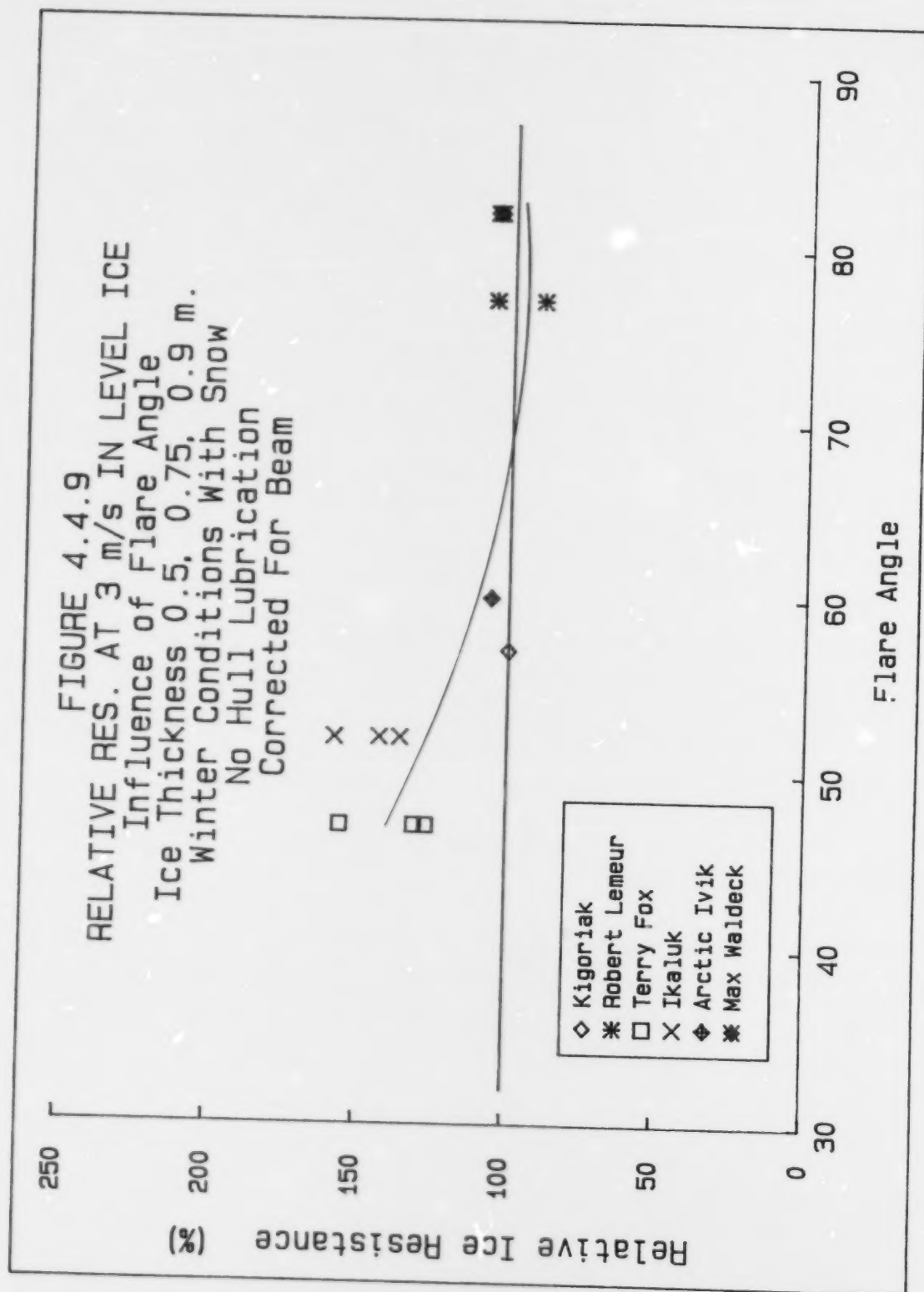


FIGURE 4.4.10  
RESISTANCE INCREASE FROM 1 TO 3 m/s  
Winter Conditions With Snow  
No Hull Lubrication  
Corrected For Beam

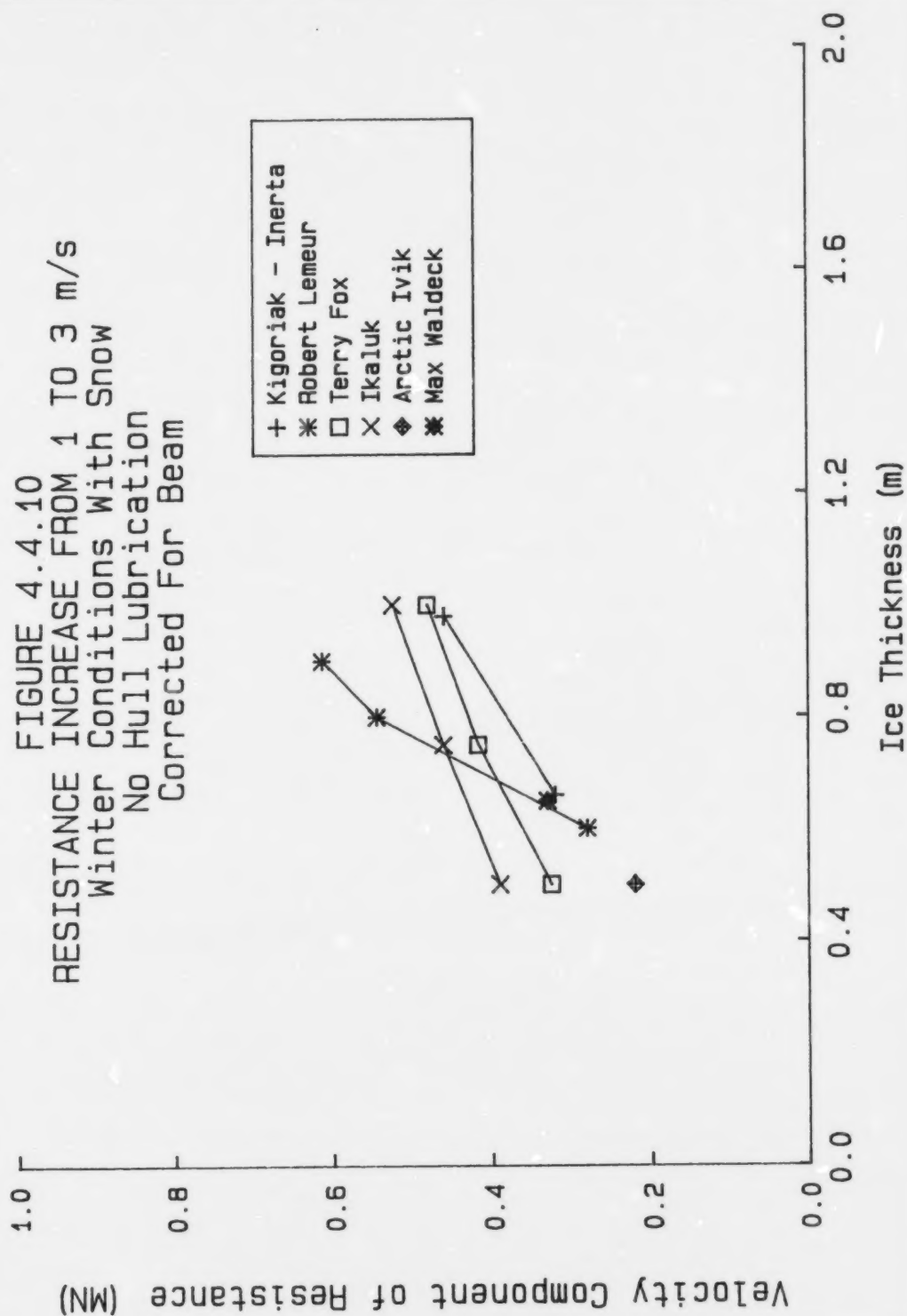
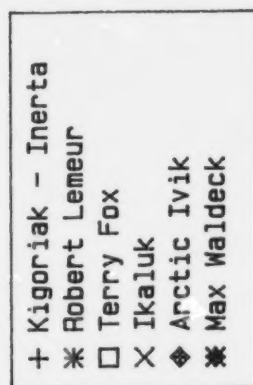


FIGURE 4.4.11  
RESISTANCE PER TONNE DISPLACEMENT, 1 m/s  
Winter Conditions With Snow  
No Hull Lubrication  
No Correction For Beam

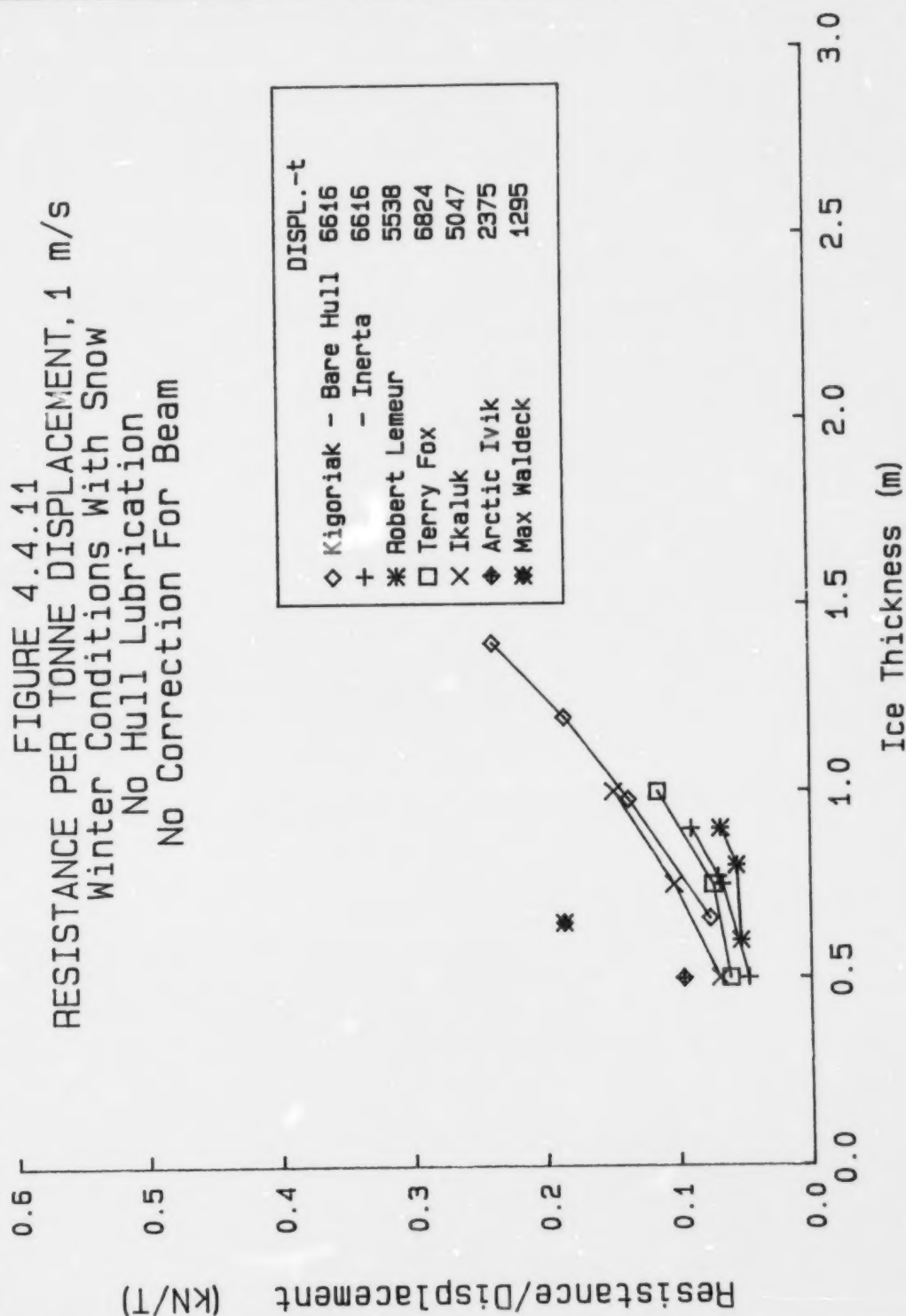




FIGURE 4.4.12  
RESISTANCE PER TONNE DISPLACEMENT, 3 m/s  
Winter Conditions With Snow  
No Hull Lubrication  
No Correction For Beam

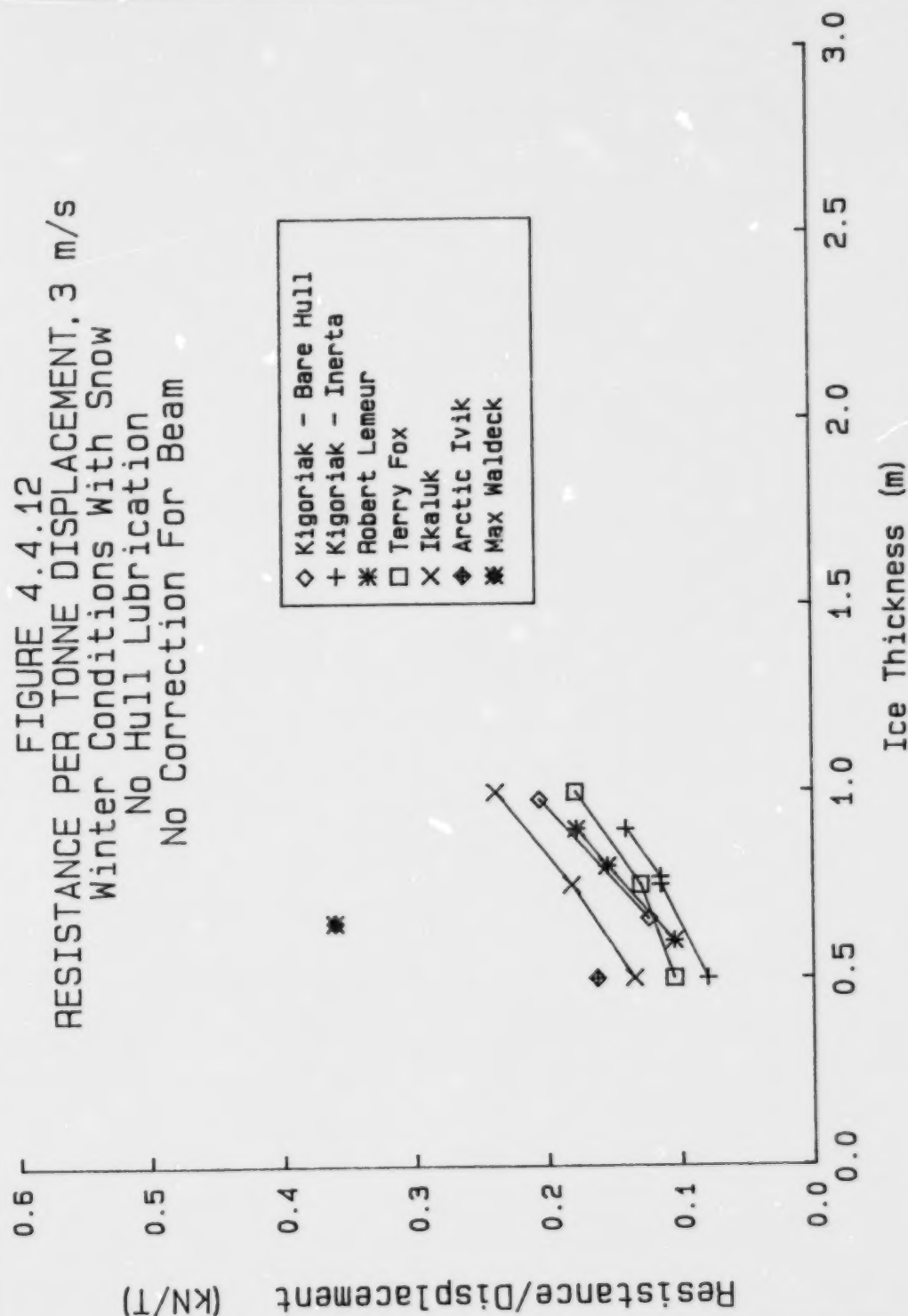
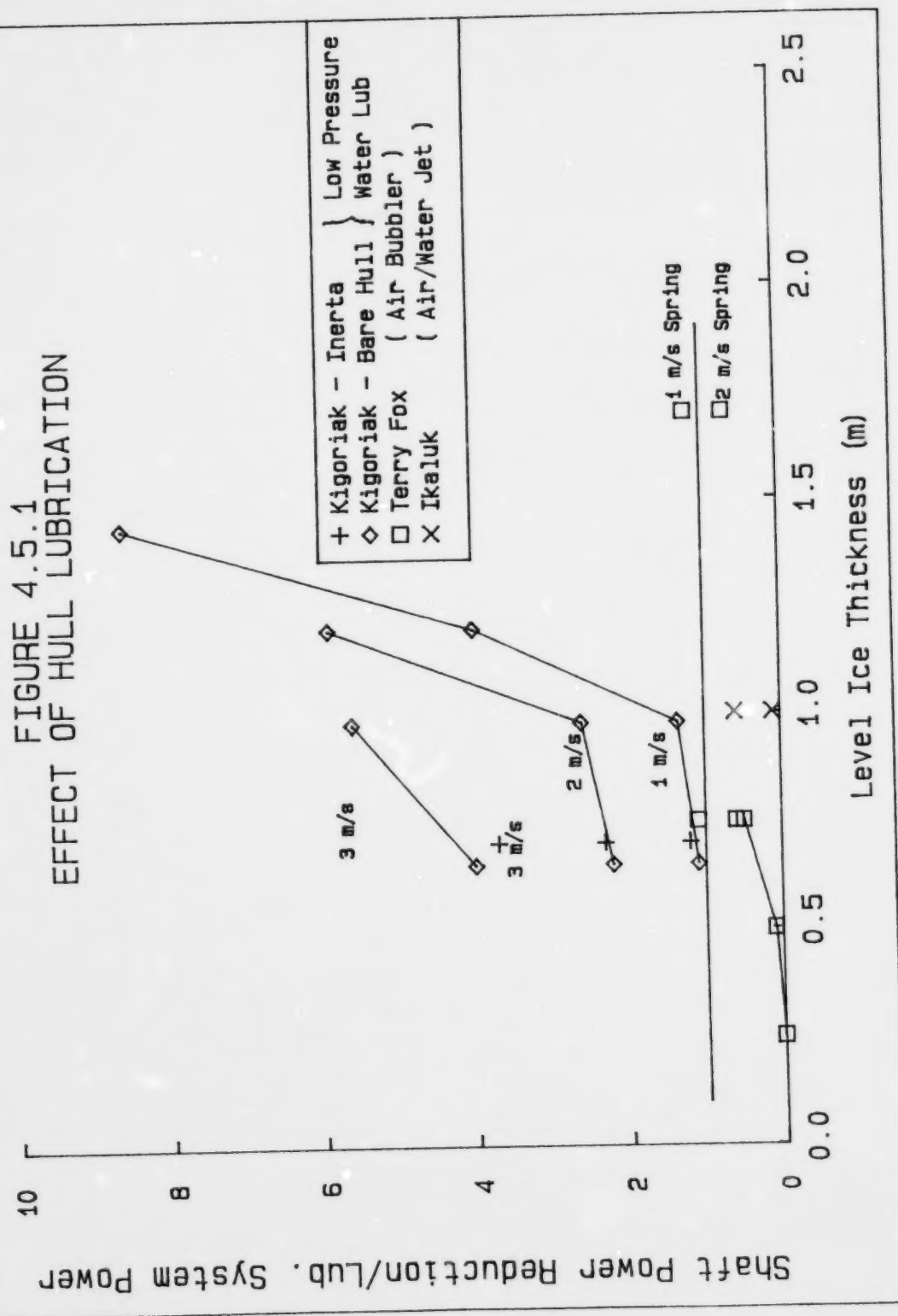
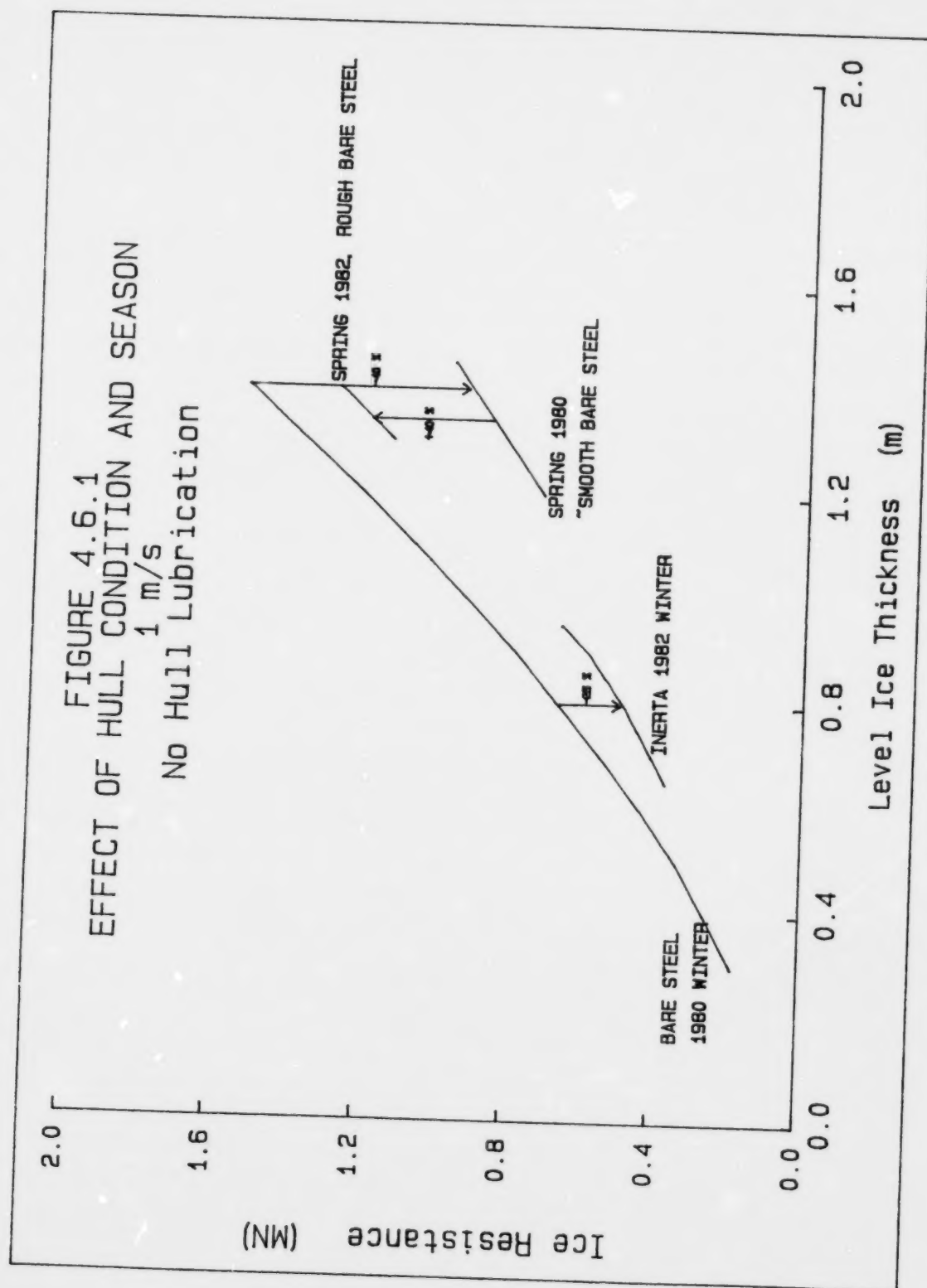


FIGURE 4.5.1  
EFFECT OF HULL LUBRICATION





## 5.0 CHANNEL PERFORMANCE

### 5.1 General

There are only limited data available for the performance of the vessels in channels, and where they are available, the properties of the channels - coverage and ice piece size, etc. - have not been documented. Therefore, the performance of the vessels cannot be related to the channel properties, other than by the general categorization of newly broken channels.

Data are available for the Kigoriak and Ikaluk in Winter ice and for the Kalvik in thick deteriorated ice. In each case, limited data of ship speed versus power, ahead and astern in a channel newly broken by the subject ship in level ice, are available.

The means of comparison selected is for the power or resistance in the channel at a particular speed to be compared with the power or resistance in breaking the same level ice at the same speed. Since there are no data available for level icebreaking performance astern, power or resistance for ahead level icebreaking is used for both channel ahead and astern comparisons.

Notwithstanding the fact that channel properties are not known, it is anticipated that the analysis will give some indication of relative channel performance.

### 5.2 Analysis

Power versus speed data for Kigoriak, Ikaluk and Kalvik (Terry Fox) in ahead level icebreaking and channel tests are given for test level ice thicknesses in Table 5.1 (D). No hull lubrication systems are operating and no ship beam correction is applied. These data are translated into resistance and the ratio of resistance in the channel ahead/resistance in level icebreaking ahead in the same ice is given. Channel resistance data for Kigoriak, Kalvik and Ikaluk are given in Figure 5.1 and the relative resistance data in Figure 5.2.

Power versus speed data for the vessels moving astern in the broken channel and ahead at the same speeds in the same unbroken ice are given in Table 5.2 (D). In this case, power astern to resistance astern conversion data are not available for the vessels, so that the relative performance is given as power astern in channel/power in level icebreaking ahead at the same speed in the same ice. This ratio is plotted in Figure 5.3.

### 5.3 Results

Figure 5.1 shows the resistance of Kigoriak, Kalvik and Ikaluk ahead in their newly broken channels. It is noted that resistance increases generally with speed and ice thickness. Considering the lack of knowledge of the track conditions, it is not possible to infer any specific difference in channel performance ahead between the vessels. It is noted, however, that the low speed resistance for Kigoriak is high relative to that for Kalvik. It is considered that this is due to the adfreeze effect which causes an accumulation of ice at the bow when moving at low speeds through broken ice in cold conditions. Kigoriak was in such Winter conditions, whereas the Kalvik data are for warmer Spring/Fall conditions.

The relative resistance comparison between the channel condition ahead and level ice ahead is shown in Figure 5.2. The Kigoriak and Ikaluk data appear to follow similar trends, but the equivalent Kalvik data in thick deteriorated ice do not, either in terms of magnitude or the effect of speed.

The magnitude of the ratio, resistance in channel/resistance in level ice, has a possible explanation, which is that level ice resistance is greatly affected by ice strength, whereas channel resistance is probably not. Consequently, it would be more appropriate to use level ice resistance ahead in Winter ice for this comparison. This is estimated using resistance data and ice thickness exponents from Section 4.0 and the appropriate ratios are shown in Figure 5.2. The results appear more in keeping with those of Kigoriak and Ikaluk.

As in the case of absolute resistance, only broad trends should be deduced from this presentation. It is evident that there is a measure of similarity between the vessels for channel resistance/level ice resistance versus ice thickness.

These data might be applied in the following manner. If it is assumed that one of the vessels is escorting a vessel of similar but no greater beam through ice of, say, 1.5m thick, then the resistance of the escorted vessel will be of the order of one-third that of the escort vessel. This ratio can be corrected to an approximate power requirement depending upon the relative efficiencies of the two vessels propulsion systems.

The data for channel performance astern in Figure 5.3 provide some valuable insight into backing astern which is particularly relevant to the ramming cycle. Generally speaking, for Kigoriak and Ikaluk, the astern mode in the broken channel, at low speeds and in thin ice, requires less power than breaking level ice ahead. However, in thicker ice and at higher speeds, the power required to back can be far higher than level icebreaking power ahead at the same speed.



All vessels in the group have square supply vessel sterns which are poor ice clearing devices. The magnitude of the power required for astern performance is considered, however, to be largely due to propeller ice interaction in clogging and blocking of the nozzles. The Kigoriak has an anomalous point at 1 m/s in 1.56m of ice. The backing power is considerably lower than might be expected from the other results. The explanation is that astern power was applied slowly and cautiously, thereby avoiding the worst effects of nozzle blocking. The result was more satisfactory performance astern. This demonstrates that the performance astern is sensitive to blockage of nozzled propellers of these ships.

The data point for Kalvik is extremely revealing. Using either Winter or Spring/Fall level ice power, the power required for backing in broken channel is only one-third that required for ahead level icebreaking and only one-half that of the best nozzle vessel performance. This demonstrates clearly the advantage of the open propeller vessel in avoiding the retarding effects experienced by the nozzled vessel due to propeller ice interaction when going astern.

#### 5.4 Conclusions

Due to the limited data available for vessels in the group, their performance in newly broken channels can only be analyzed for broad trends.

Resistance of the vessels in their own newly broken channels increases with ice thickness and with speed and points to a vessel being escorted through a freshly broken channel in thick ice requiring approximately one-third the power of the escort icebreaker.

In the astern mode, in a newly broken channel in thick ice or at relatively high speed, vessels with ducted propellers may require higher power than required to break the same ice going ahead. Skillful application of astern thrust can, however, control the degree of propeller-ice interaction with the nozzle and provide more efficient backing operation.

The open screw propulsion system, as on the Kalvik, is clearly most beneficial in avoiding the worst retarding effects of propeller-ice interaction. Open screw propulsion astern would appear to be at least twice as efficient as for ducted vessels.

FIGURE 5.1  
CHANNEL PERFORMANCE AHEAD  
Resistance In Newly Broken Channel

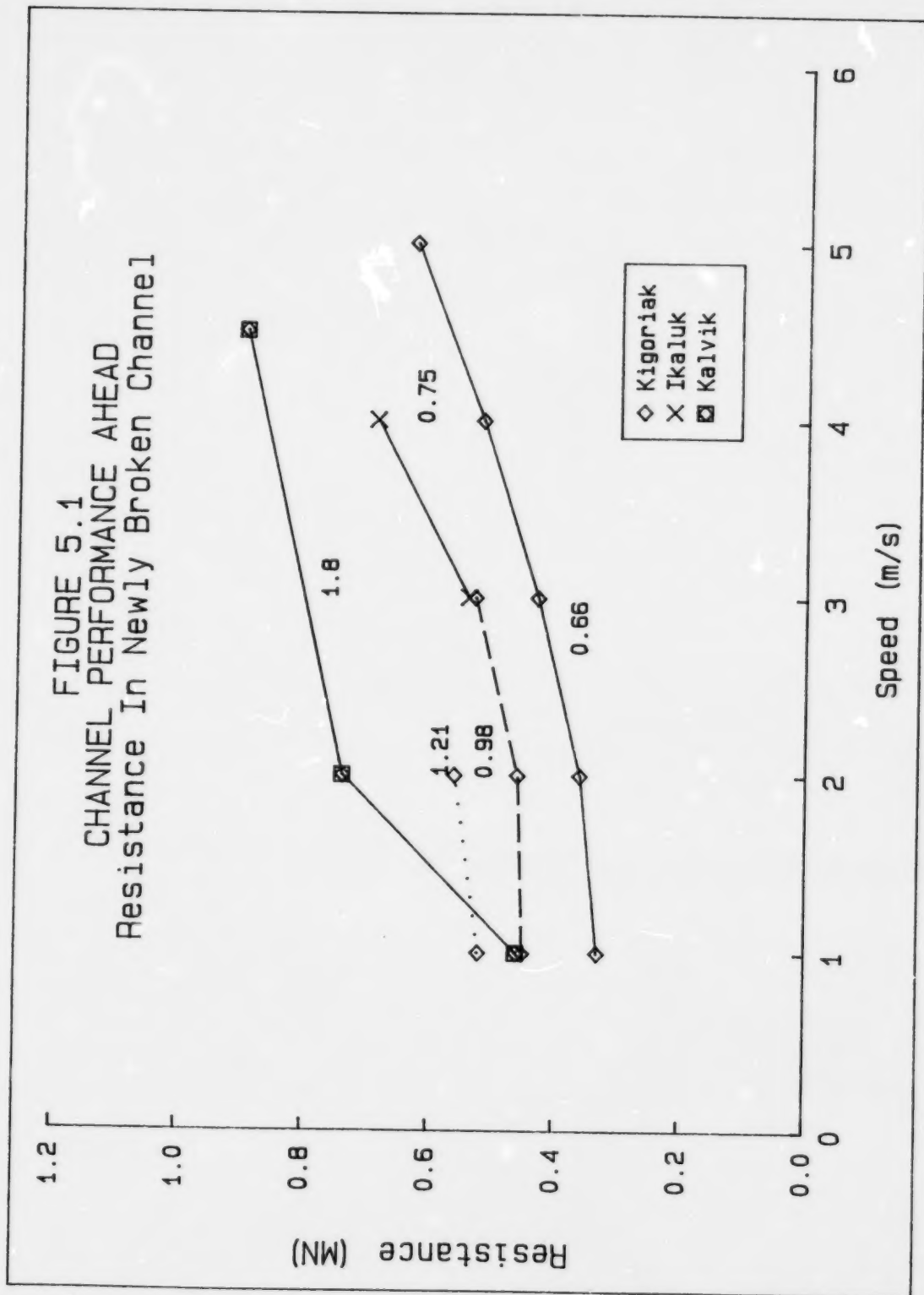


FIGURE 5.2  
CHANNEL PERFORMANCE AHEAD  
Channel Resistance /  
Level Icebreaking Resistance  
At Same Speed In Same Ice  
Newly Broken Channel

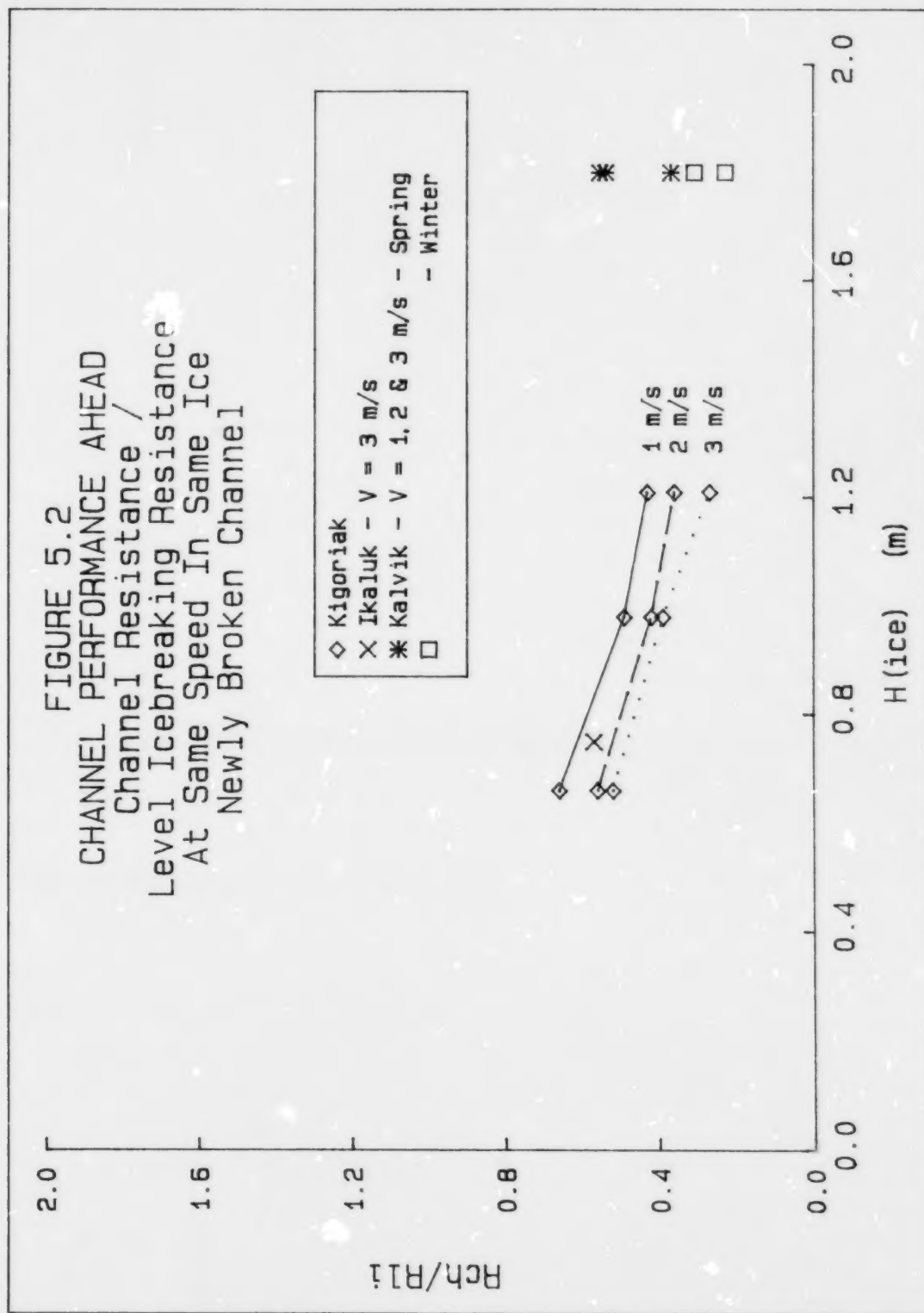
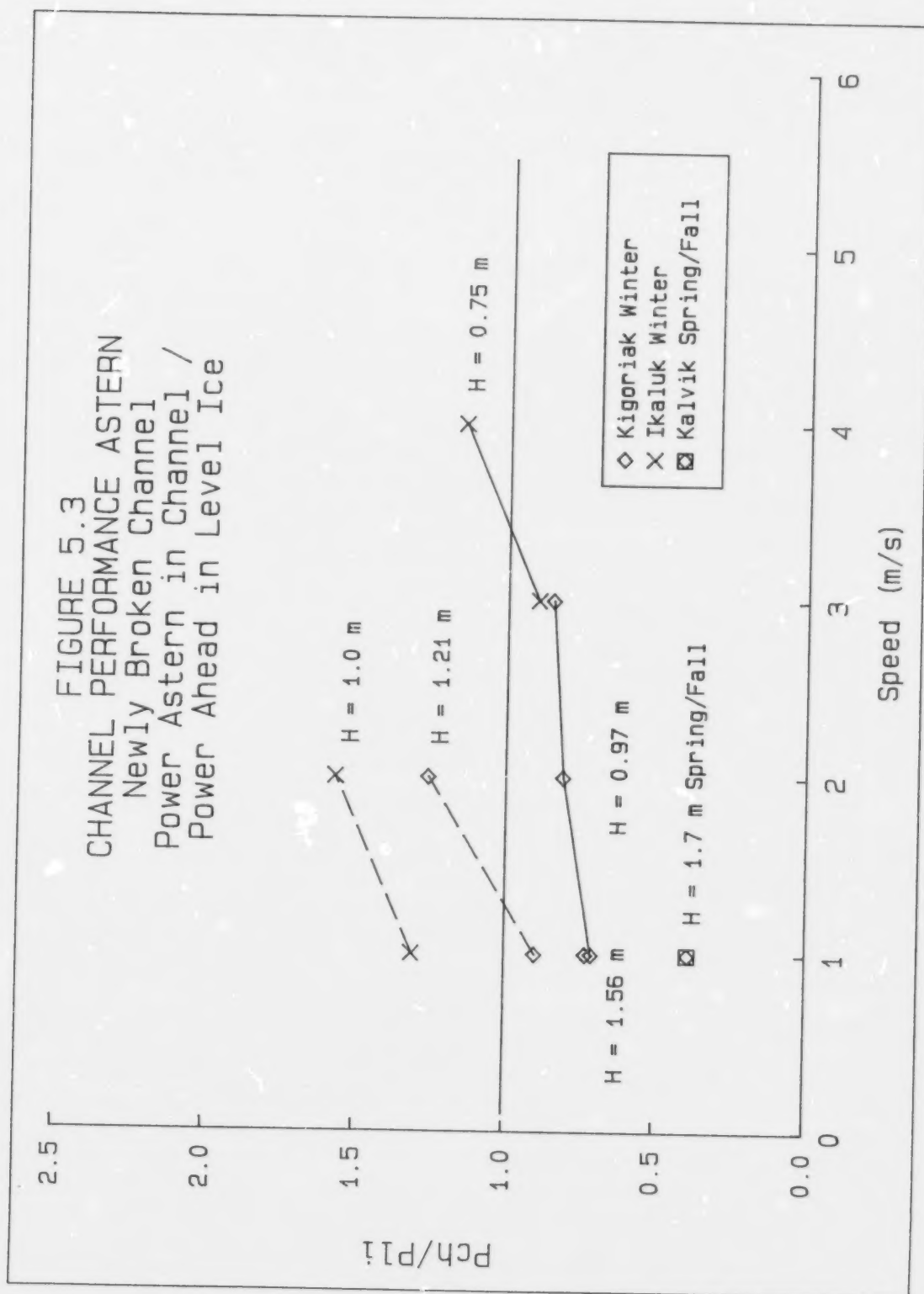


FIGURE 5.3  
CHANNEL PERFORMANCE ASTERN  
Newly Broken Channel  
Power Astern in Channel /  
Power Ahead in Level Ice



## 6.0 MANOEUVRING PERFORMANCE

### 6.1 Introduction

The available full scale data for icebreakers in the group allow comparisons to be made for their performance in the following manoeuvres:

- turning circle ahead
- breakout of channel ahead
- Captains or Star manoeuvre

Turning circle diameter is the traditional and simplest way of expressing the ability of a vessel to change its heading. Generally speaking, the smaller the turning circle, the greater the capability to follow the optimum route and avoid difficult or hazardous features while in continuous motion.

When such continuous motion is stopped, either voluntarily or involuntarily, it may be required to back up and change direction ahead by breaking directly out of the broken channel. The relative ability to carry out this manoeuvre enhances general icegoing ability and can compensate for any limitations in steady turning ahead.

Where large changes in heading are required within a relatively small space, this is effected by the Captains or Star Manoeuvre, the equivalent of the automobile's three or multi-point turn. Again, ability to effect this manoeuvre enhances icegoing ability and can compensate for limitations in carrying out other manoeuvres.

Taken overall, these three manoeuvres provide a basic measure of a vessel's steering and manoeuvring capabilities, particularly as they affect the missions of transit and ice management. In other missions such as escort, additional manoeuvring qualities can become relatively more important. The ability to back in ice under directional control and to move close alongside a beset vessel would be two of these. Such characteristics are not a high priority for the vessels in this group and have not been tested.

Manoeuvrability astern could not be addressed due to a lack of full scale data.



## 6.2 Turning Circle Ahead

### 6.2.1 General

Turning circle trials are normally carried out in level ice at full power and with full rudder, the vessel being in an initially upright condition. Data for such trials, although limited in some cases, are available for all vessels in the group. Turning may also be enhanced by heeling the vessel and data on this effect are available for Kigoriak and Robert Lemeur.

In this analysis, the first stage is to compile and compare the turning circle diameters of the vessels in the level ice thicknesses for which tests have been carried out. These data are for each vessel in an initially upright condition at full or close to full power and with full rudder. The data are for both Winter and Spring/Fall ice conditions with snow cover. Except for Terry Fox, twin screw vessels have equal power on the shafts. Shortage of data in thick ice for Terry Fox has meant the use of test results with 12% power differential on the shafts. The mean diameter of two tests turning to starboard, with power differential to port and then to starboard, is used.

The data are then non-dimensionalized such that meaningful comparisons of turning performance relative to vessel form and features can be made as independently as possible of vessel size, power and environmental conditions. Such comparisons are then carried out. Finally, the effect of heel is presented for the vessels Kigoriak and Robert Lemeur.

### 6.2.2 Data Analysis

Turning circle data for full or close to full power, full rudder, zero initial heel and the noted environmental conditions are given in Table 6.1 (D) and presented in Figure 6.1. In addition to the tabulated data, seven tests were carried out for Kigoriak in June, 1980. They are not reported individually, but resulted in the mean curve shown in Figure 6.1. These tests were carried out both with and without the water wash system operating. It is reported that this had no discernible effect upon turning diameter.

The data are non-dimensionalized in the following manner. Turning circle diameter is expressed relative to ship waterline length, D/L. This allows comparisons to be made between different sizes of ship.

Ice thickness is expressed as the ratio of the test ice thickness to the icebreaking capability of the vessel at 1 m/s

in ice with the test ice properties. This makes the data as independent as is possible of vessel power and environmental conditions and is roughly equivalent to non-dimensionalizing with respect to speed into the turn, which is considered a significant factor in turning performance. Speed data are only reported in a few cases such that direct allowance cannot be made. The data analyzed in this manner are given in Table 6.2 (D) and presented in Figure 6.2.

The non-dimensionalized data are now compared for the effect of design features on turning performance. Three of the vessels, Kigoriak, Robert Lemeur and Max Waldeck have reamers and in order to investigate their effect, Figure 6.3 is derived. Non-dimensional turning diameter is plotted against the ratio reamer width/length of parallel side, at a non-dimensional ice thickness of 60% of 1 m/s icebreaking thickness.

Finally, the effect of heel on Kigoriak and Robert Lemeur is analyzed and presented in Figure 6.3. Turning diameter at different combination of rudder angle and heel angle are given non-dimensionally relative to the turning diameter at zero heel and full rudder.

#### 6.2.3 Results

The results for absolute size of turning circles in Figure 6.1 (D) show that the Max Waldeck turns in less room than the other vessels. Kigoriak is next, followed by Robert Lemeur, Kalvik and Arctic Ivik. No results are available for Ikaluk beyond 0.35m ice thickness, the reference in test report noting that turning in thicker ice was so slow that meaningful data could not be obtained.

All the results for Kigoriak in Winter conditions fall upon a well defined straight line. A data point for Spring ice, with reduced power and a badly deteriorated steel hull surface, is somewhat higher. Data for Robert Lemeur and Terry Fox in thick ice, see Figure 6.1, are noted as Spring/Fall conditions and are positioned below a straight line passing through Winter results in thinner ice.

Non-dimensionalization of data, as given in Figure 6.2, improves the data presentation in that the range of the curves is more uniform and the plots for Robert Lemeur and Terry Fox are closer to a straight line relationship. The relative order of turning capability, expressed non-dimensionally, is the same as in the absolute turning diameter presentation, Figure 6.1.

The presentation of non-dimensional turning diameter versus reamer width per unit length of parallel side, Figure 6.2 is extremely revealing. There is a very clear and close to

linear relationship of improved turning with increased relative width of reamer. Terry Fox and Arctic Ivik do not have reamers and their data lie on the major vertical axis.

In order to turn in ice while going ahead, a vessel must be able to rotate in the track broken by the bow. For the vessels with reamers, this is achieved by the stern swinging over in the track to an angle in radians proportional to reamer width/length of parallel side. The relationship in Figure 6.2 shows that the turning diameter is an approximately linear function of the yaw angle given the reamer design.

For vessels without reamers, any appreciable rotation in the track can occur only because the bow, through cusping action, breaks a track wider than itself. The degree to which the vessel may now rotate is governed strongly by its waterline shape relative to track width in excess of bow width. There is no satisfactory method yet developed for defining this curvature as it might affect rotation in the track or turning ability. Length to beam ratio and length of parallel midbody are known to play an important, yet not exclusive or consistent, role. Moreover, there is presently no reliable method of relating track width/vessel beam to ship design features. Rotation in the track can also be augmented by ice-breaking and crushing where the hull bears against the ice edge. It would be expected that the rudder turning force and waterline slope would be important factors in this respect.

Many of the factors with probable impact upon turning ability as described above are given for the vessels below.

|               | D/L    | REAMER<br>WIDTH<br>% /L | L/B | PARALLEL<br>MIDBODY<br>Lpp/L | TURNING<br>FORCE<br>COEFF* | SIDE<br>SLOPE |
|---------------|--------|-------------------------|-----|------------------------------|----------------------------|---------------|
| Max Waldeck   | 7.5    | 2.5                     | 3.6 | 0.67                         | 0.63                       | 0             |
| Kigoriak      | 12.5   | 1.8                     | 4.4 | 0.67                         | 1.52                       | 0             |
| Robert Lemeur | 18     | 1.1                     | 4.2 | 0.63                         | 0.90                       | 0             |
| Terry Fox     | 34     | 0                       | 4.7 | 0.35                         | 0.4                        | 8             |
| Arctic Ivik   | 48     | 0                       | 4.6 | 0.79                         | 0.95                       | 0             |
| Ikaluk        | V.Lge. | 0                       | 4.6 | 0.62                         | 0.81                       | 8             |

\* This coefficient is adopted from (34) as an approximate expression of rudder turning force as a function of propeller size and thrust, rudder size and location.

D = Turning diameter (m)  
 L = Length of waterline (m)  
 B = maximum beam at waterline (m)  
 Lpp = Length of parallel midbody (m)

It is noted that both Terry Fox and Arctic Ivik have very

similar L/B ratios. Relative to Arctic Ivik, Terry Fox has less than half the parallel midbody length and an 8 degree side slope, but less than half the turning force. The result is that Terry Fox turns 30% better than Arctic Ivik. Therefore, in this comparison, waterline shape and/or side slope appear to dominate over turning force.

Ikaluk has the same side slope as Terry Fox, twice the turning force and twice the midbody length. Her turning ability is significantly worse than that of Arctic Ivik. This information suggests that waterline shape is dominant over turning force.

It is known that many icebreakers, and in particular escort icebreakers, turn well, with D/L values in the same range as the reamed vessels. The addition of their data, analyzed in this same non-dimensionalized manner, should advance understanding of the turning mechanism.

Considering the reamed vessels, Kigoriak has a significantly higher turning force than Robert Lemeur, which is again higher than that of Max Waldeck. Yet Max Waldeck turns very much better than Robert Lemeur. This would indicate that, for the reamed vessels, turning moment is not a significant factor once sufficient turning force is provided.

The significant effect that heel can have on turning performance is noted with reference to the data for Kigoriak and Robert Lemeur in Figures 6.3. Depending upon the local hull geometry in way of the waterline, heel in the same direction as the rudder can either assist or impede turning. The explanation is that heel modifies the flare angle (measured between the section tangent at the waterline and vertical) distribution around the waterline. At the bow, a net side force is exerted from the side with lower average flare angles to that with higher flare angles. This, in turn, can produce increased lateral icebreaking at the bow. Likewise, flare angle at the outer stern quarter will be modified from the upright condition and will allow either more or less icebreaking to occur. Moreover, the length of parallel side at the waterline may change. Hull can therefore modify drift angle and subsequently turning diameter. With a conventional, fully formed hull the effect of heel will normally be to augment the turn in the direction of heel. However, contemporary forms such as Kigoriak and Robert Lemeur with chines and reamers can behave differently.

Kigoriak's response to heel is significant. As noted in Figure 6.3, increasing heel angle in the same direction as the rudder enhances turning in a linear fashion, the turning circle reduction at 6° heel being about 60 percent. When the rudder is centered and heel is applied, the Kigoriak turns about equally well in the direction of heel as it would turn with the rudder alone.



Robert Lemeur, Figure 6.3, heel in the direction of the rudder assists turning in that direction, although to nowhere near to the extent found with Kigoriak. Here, 6 degrees heel angle results in 25% reduction in turning diameter. However, another phenomenon is seen when the ship is also trimmed to the bow by about 0.5 meters. The bow submerges another chine-which causes on the outside of the heel in the bow a close to vertical section to be interacting with the unbroken ice. Then the turning circle is even smaller, by 20 percent, than heeled without the chine submerged, but in the opposite direction.

It is, therefore, clear that heel is a powerful aid in turning, but the effect cannot be automatically assumed.

#### **6.2.4 Conclusions**

The turning circle data for the vessels have been presented in a non-dimensional format allowing the effect of hull form and features on turning performance to be investigated irrespective of vessel, size, power and test conditions.

For vessels with reamers, the turning diameters is an approximately linear function of the ratio of reamer width to length of parallel side. Relative to reamer geometry, high rudder turning force is not a significant factor in the ice thicknesses where tests were performed.

In considering the relative turning abilities of Terry Fox, Ikaluk and Arctic Ivik, waterline shape and/or side slope appear to dominate over turning moment. The addition of data from other icebreakers without reamers, to be analyzed in the same non-dimensional manner, would advance the understanding of the turning mechanism.

Heel angle can reduce turning circle by 50% or more. However, the effect cannot be automatically assumed. It is dependent upon local hull geometry in way of the waterline which can change rapidly with draft and trim. This is especially true for contemporary vessels with chines and reamers.

### **6.3 Channel Breakout Ahead**

#### **6.3.1 General**

This manoeuvre measures the distance required for a ship to breakout of its own freshly broken channel from a stopped position. Full power and full rudder are used. At the completion of the manoeuvre the whole ship should be clear of the channel.



Channel breakout trials exist for the following ships:

- Kigoriak
- Terry Fox
- Robert Lemeur
- Ikaluk

All the trials have not been carried out using the same methodology, particularly with regard to the position of the ship at the end of the trial. This may introduce slight differences in the measured channel breakout distances expressed in terms of ship lengths.

The full data set is shown in Appendix D.

### **6.3.2 Data Analysis and Conclusions**

All the available data has been shown on figure 6.4, plotted as a band width within which all the data lies. The upper end of the right line (above about 1.4 m ice thickness) is determined by the spring/fall breakout tests. The lower end of this line is determined by the most capable of the ships (Kigoriak) in winter. The left hand bound is determined by the least capable of the ships (Ikaluk) in winter.

The data are not sufficient in number and quality to draw conclusions about the effect of design features on the breakout performance. The plot does however show trends.

As the channel breakout involves many of the same performance requirements as the turning circle it would be expected that the ships would have similar rankings. The Kigoriak appears to be the most effective. The Kigoriak reaches its winter breakout limit in ice thicknesses of 1.2 to 1.4 metres. Breakout in the weaker summer ice is clearly easier than in an equivalent thickness of winter ice.

## **6.4 Captain's Manoeuvre (Star Turn)**

### **6.4.1 General**

This manoeuvre is an alternative to the turning circle as it requires a smaller radius to effect a change in direction of 180 degrees. It involves turning while using a succession of ahead and astern manoeuvres. When backing ability is limited this manoeuvre is important for escort icebreakers to assist the ship astern. It is also important when the available manoeuvring space is limited.

The effectiveness of this manoeuvre is measured by the following parameters:

- time to turn 180 degrees
- space required to effect the manoeuvre
- number of ahead and astern manoeuvres to turn 180 degrees

Data exists for the Kigoriak, Robert Lemeur and the Ikaluk. The time to turn 180 degrees and the number of manoeuvres is well documented but the required space is not.

#### 6.4.2 Data Analysis and Conclusions

The number of manoeuvres required to turn 180 degrees is shown on figure 6.5, plotted as band widths for both summer and winter manoeuvres. (The data is given in Appendix D.) The number increases with increasing ice thickness for both winter and summer ice. Fewer manoeuvres are required in summer ice than winter ice for an equal thickness. The number of manoeuvres in summer increases at a slower rate with increasing ice thickness than in winter.

For the operator one important measure of the effectiveness of this manoeuvre is the time to turn 180 degrees. Moreover if the space is available, the time to effect this manoeuvre should be assessed against the time to turn 180 degrees using the turning circle. This data is plotted on Figure 6.6.

This figure shows that the ships in this study use less than 10 minutes to turn the ship around in ice thicknesses up to 60% of their continuous ice breaking capability. In thicknesses beyond this, the time begins to increase rapidly. In the thicker ice the turning circle diameter increases rapidly whereas the width of the space required for the Captain's Manoeuvre remains more or less constant. (For ships with difficulty in channel breakout the length of the space required will increase.) The manoeuvre becomes important in thick ice with limited manoeuvring space.

For the Kigoriak the time to turn the ship around with either the turning circle or the Captain's Manoeuvre is essentially the same. The available space will therefore dictate the choice. With heeling, the choice is clearly the turning circle. However the Kigoriak is not fitted with a rapid heeling system and this alternative is not a viable option.

For the Robert Lemeur, the Captain's Manoeuvre takes longer than the turning circle in thicknesses greater than 0.40 m. This is due to the poor astern performance. The enhanced turning circle performance with heeling is not as

pronounced as on the Kigoriak and hence the choice may not be as clear cut even with the rapid heeling system fitted.

As the Ikaluk will not turn satisfactorily in ice thicknesses greater 0.15 m the only option open to the master is the Captain's Manoeuvre.

The ranking of the ships when performing the Captain's Manoeuvre is similar to the ranking in the turning circle trials. Some of the differences may however be reduced as the ships are manoeuvring in broken ice where the manoeuvrability becomes easier. This is clearly the case for the Robert Lemeur and the Ikaluk. The Ikaluk performs better than the Robert Lemeur in the Captain's Manoeuvre, yet will not turn in level ice.

FIGURE 6.1  
TURNING PERFORMANCE IN LEVEL ICE

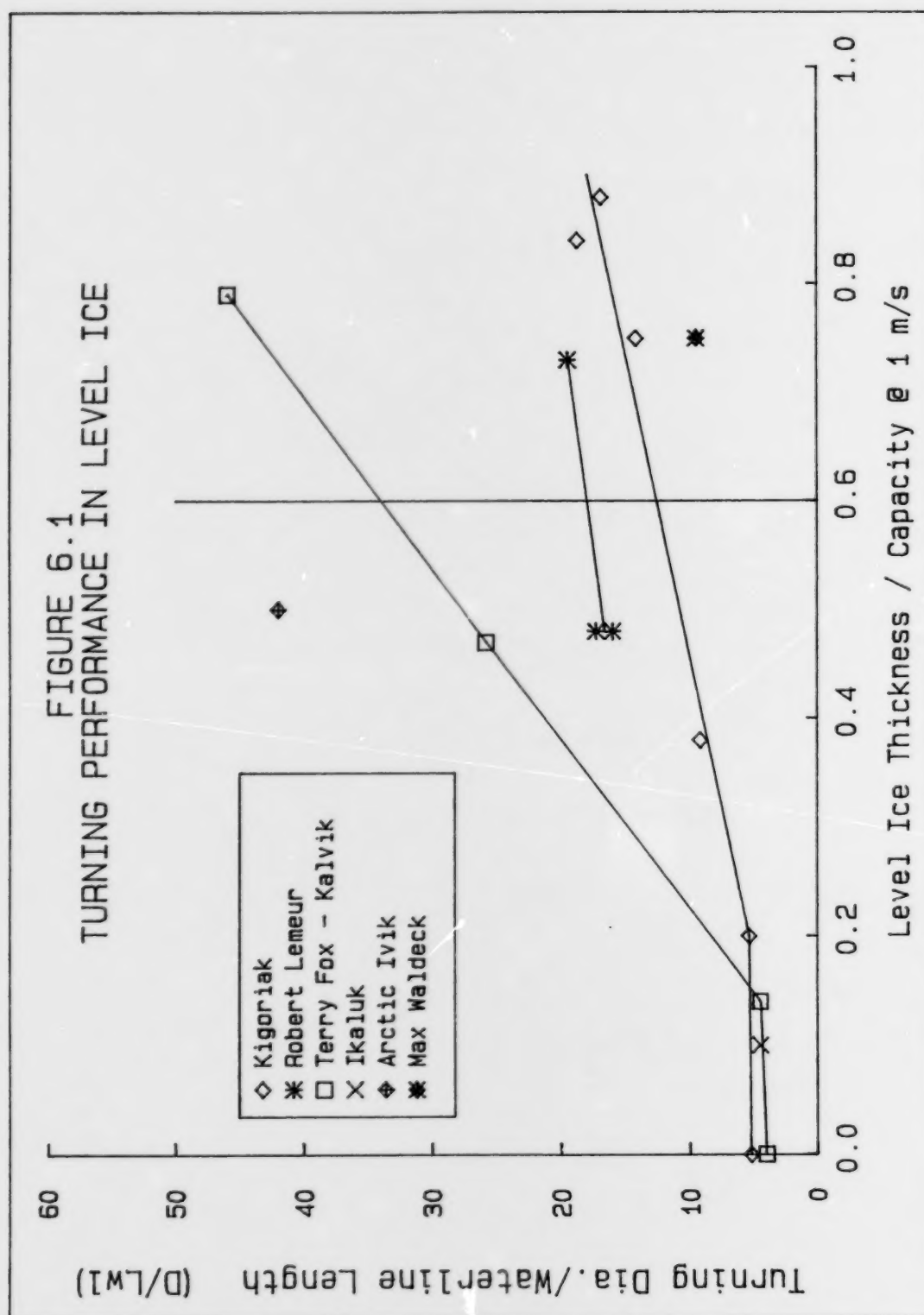


FIGURE 6.2  
TURNING PERFORMANCE - NO HEEL  
Influence of Reamers  
D/L @ 60% of 1m/s Icebreaking Thickness

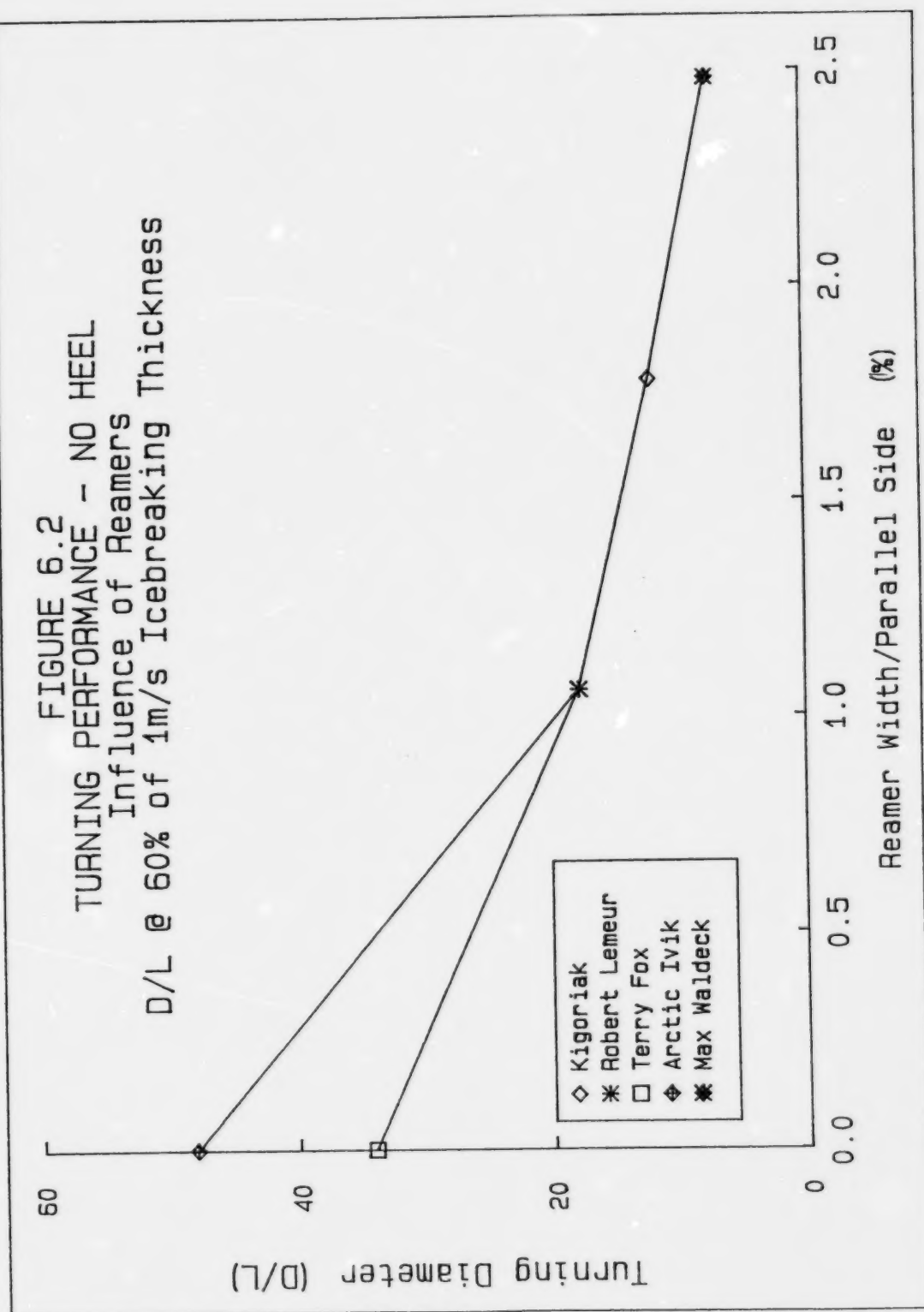




FIGURE 6.3  
EFFECT OF HEEL ON TURNING DIAMETER  
Full Power

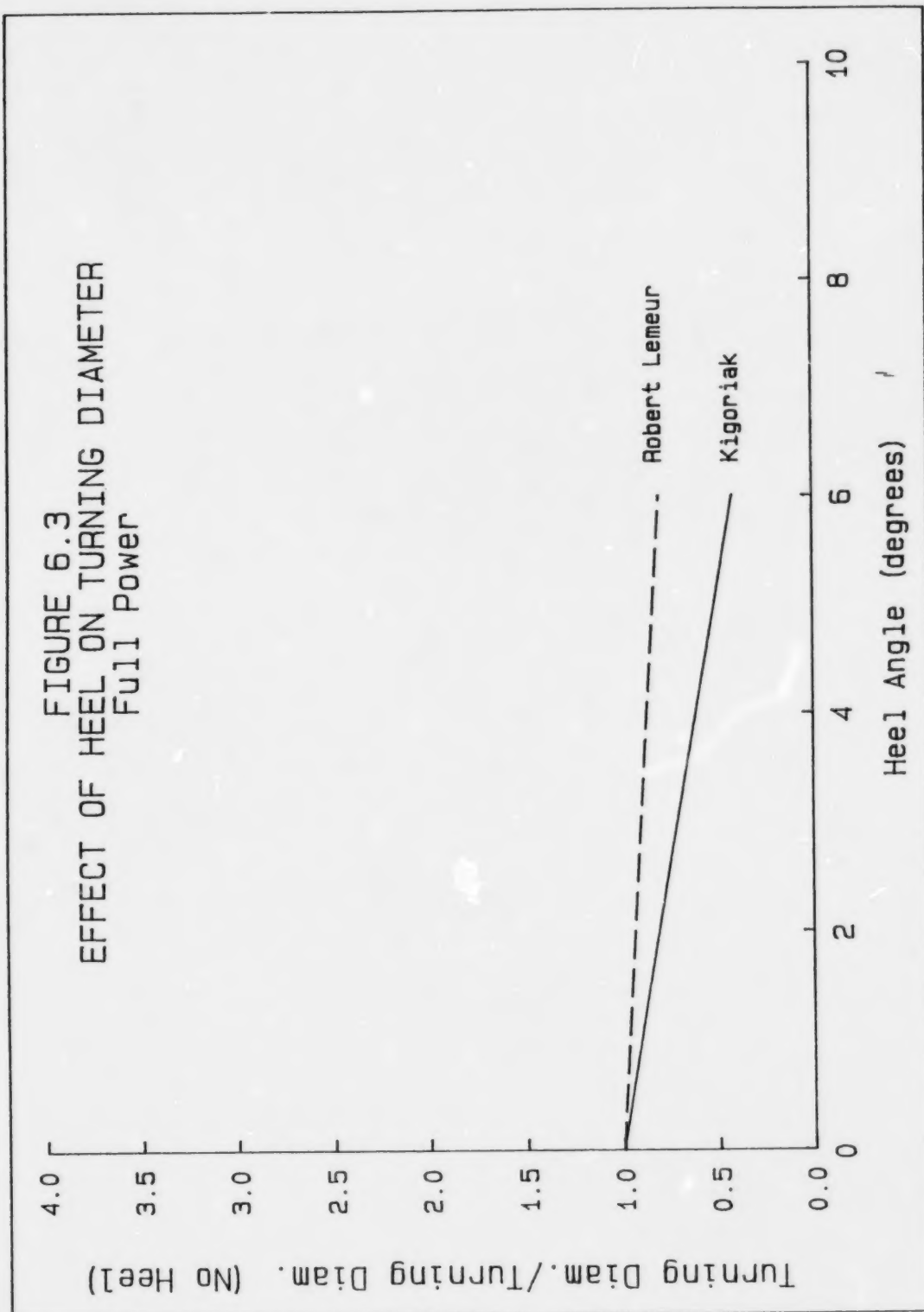
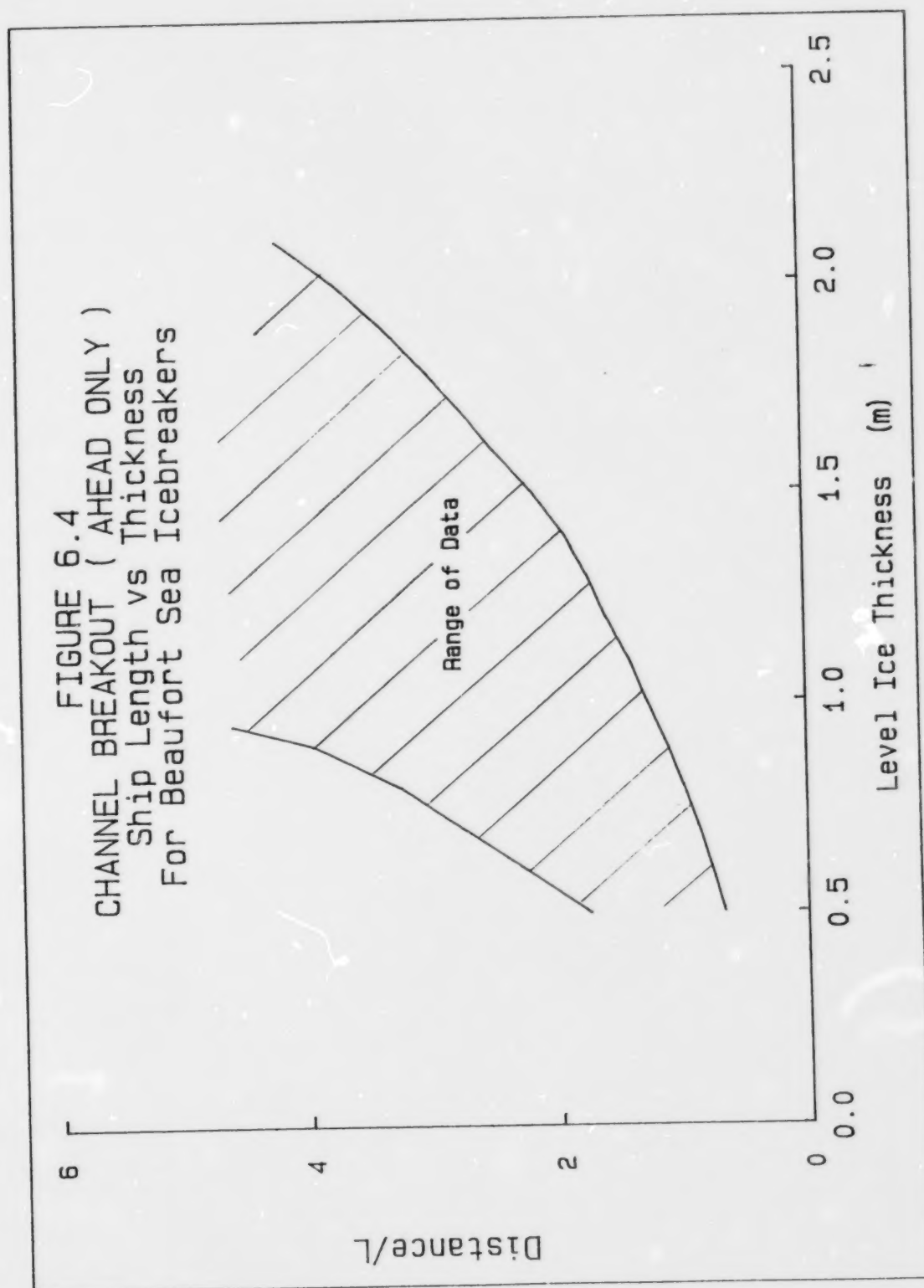


FIGURE 6.4  
CHANNEL BREAKOUT ( AHEAD ONLY )  
Ship Length vs Thickness  
For Beaufort Sea Icebreakers



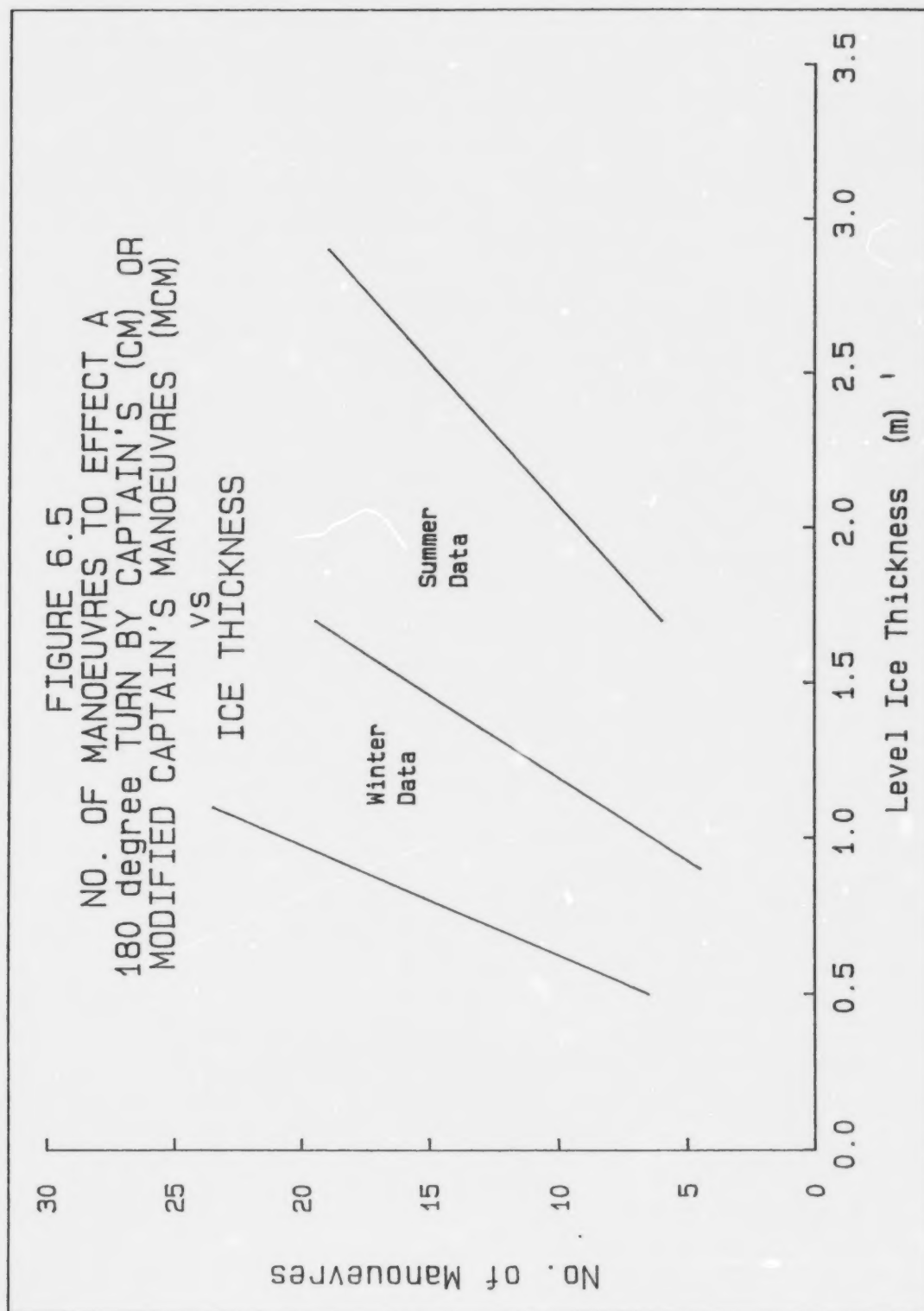
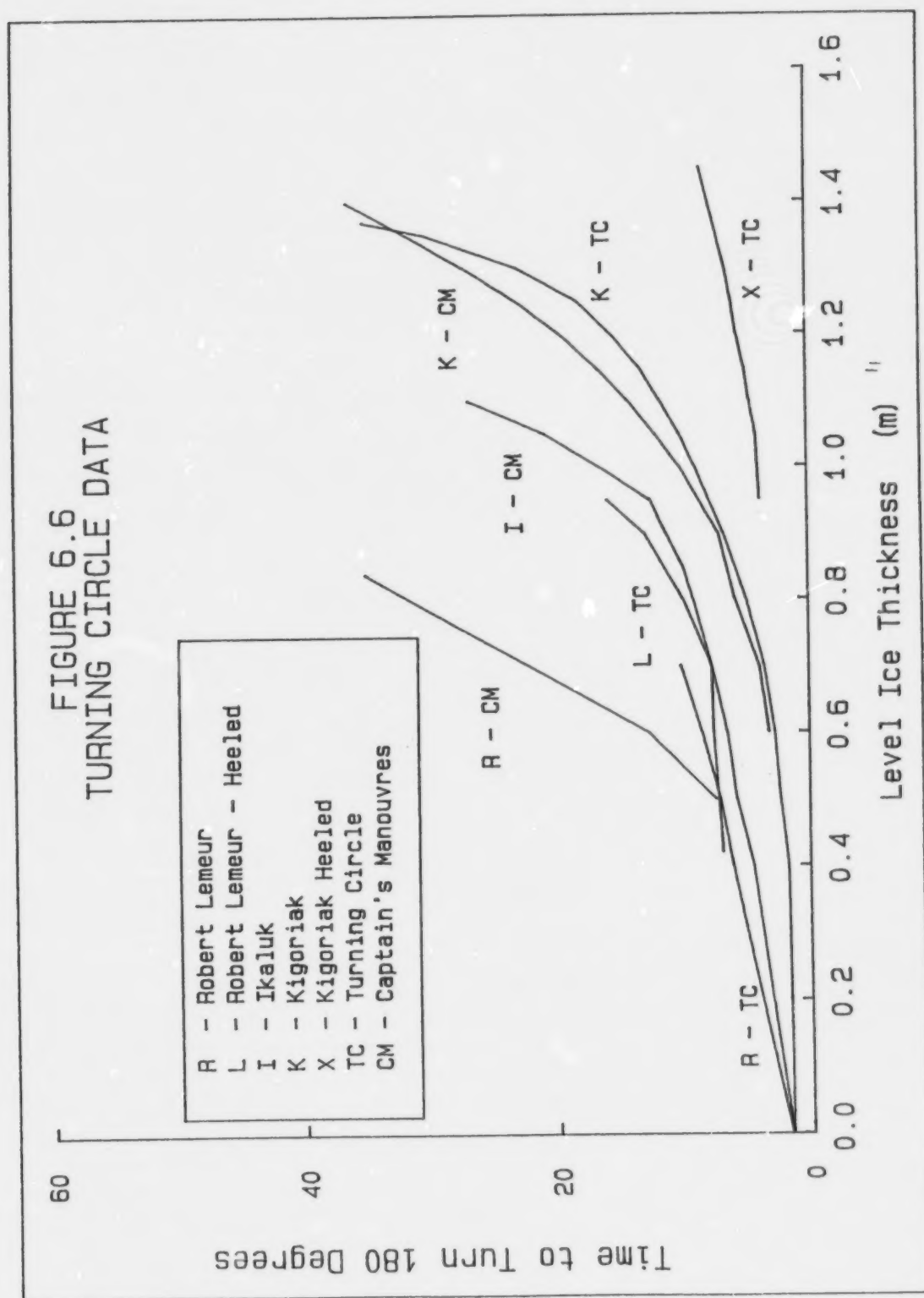
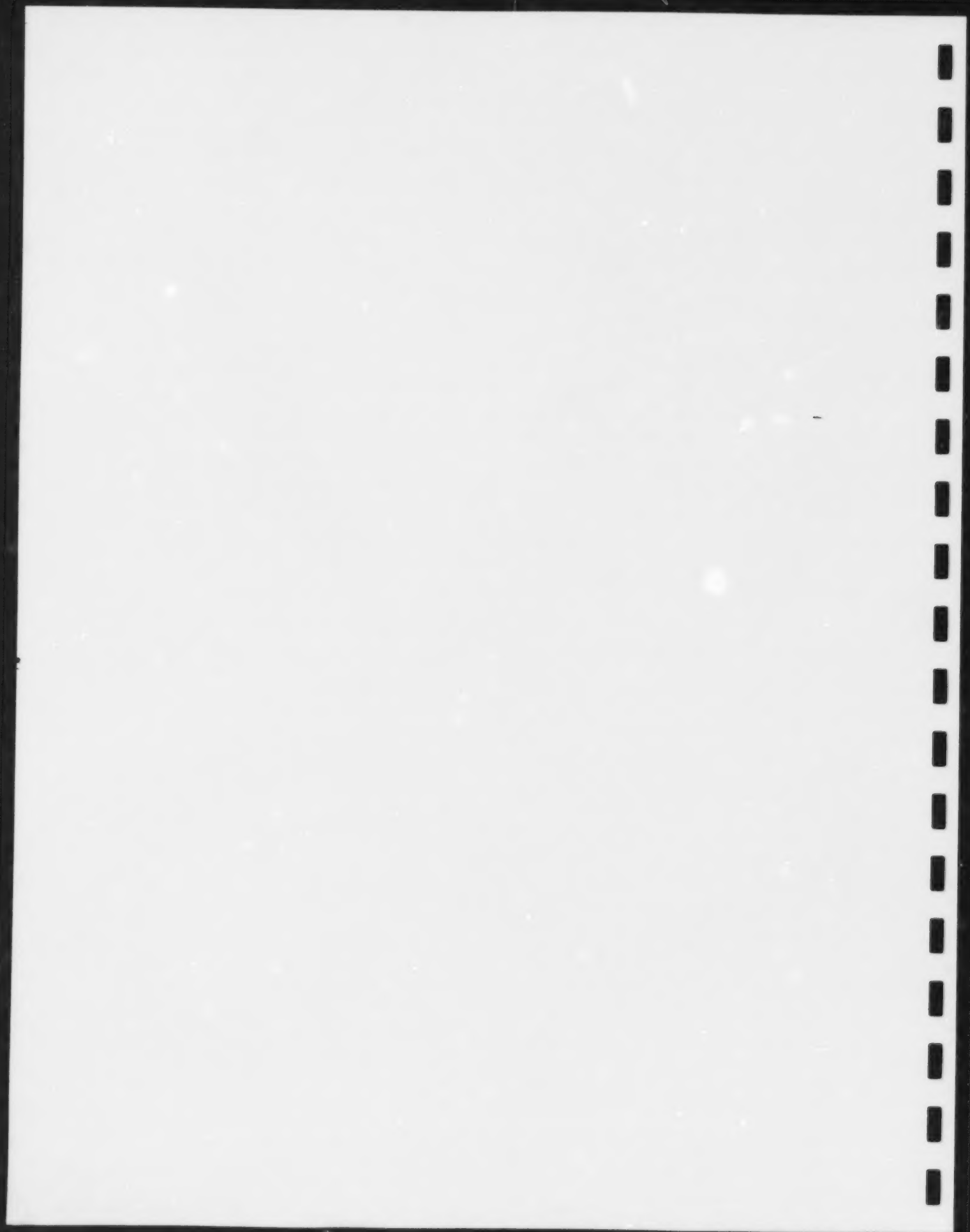


FIGURE 6.6  
TURNING CIRCLE DATA







## 7.0 OPEN WATER PERFORMANCE

### 7.1 General

Open water performance data of speed versus power for calm water conditions are available from builders' and owners' operational trials for all vessels except the Max Waldeck.

The powering data are translated into ship resistance and non-dimensional resistance vs speed curves are presented. Parametric influences are discussed.

Seakeeping tests have not been carried out on any of the vessels in this study. General seakeeping ability was however addressed in the operator interviews and assessment from the questionnaire are given in Section 3.

### 7.2 Data Analysis

The speed power data are presented in Table 7.1 (D) with reference sources.

Power is translated into resistance using the appropriate ducted or open screw propulsion data in Section 4.3 and then expressed in terms of a specific resistance coefficient, total resistance/displacement (newtons/tonnes). Speed is expressed in terms of the non-dimensional speed-length ratio Froude Number.

The specific resistance curves are shown in Figure 7.1.

### 7.3 Results

Specific resistance versus Froude Number curves for geometrically similar vessels of different size have the same shape, but the curves are displaced vertically from one another with increasing specific resistance with decrease in displacement. Furthermore, specific resistance curves for vessels of the same parent form but increasing block coefficient form a similar set of curves with resistance coefficient increasing with increase in block coefficient.

The specific resistance curves for the contemporary ice-breakers in Figure 7.1 demonstrate the above characteristics and, thereby, their generic similarities.

Terry Fox and Kigoriak, of very similar dimensions, have almost identical specific resistance curves. Ikaluk and Arctic Ivik are progressively smaller and have progressively

higher curves. The exception is Robert Lemeur which is smaller than Terry Fox and Kigoriak, but has a lower curve at low speeds. However, with the highest block coefficient of 0.7, Robert Lemeur demonstrates the expected increase in resistance coefficient at higher speeds.

Arctic Ivik and Terry Fox with the next highest block coefficients of 0.62 and 0.63, also demonstrate the expected trend to higher rates of resistance increase with speed than the lower block coefficient vessel Kigoriak (0.55) with otherwise close to similar shape and Ikaluk (0.53).

Among the vessels there are particular features, reamers and wedges, which might influence open water performance to a significant degree. Viewing the data for Kigoriak which has reamers but no important wedge with Terry Fox with a wedge but no reamers, it is evident that their influence on the open water performance can be similar.

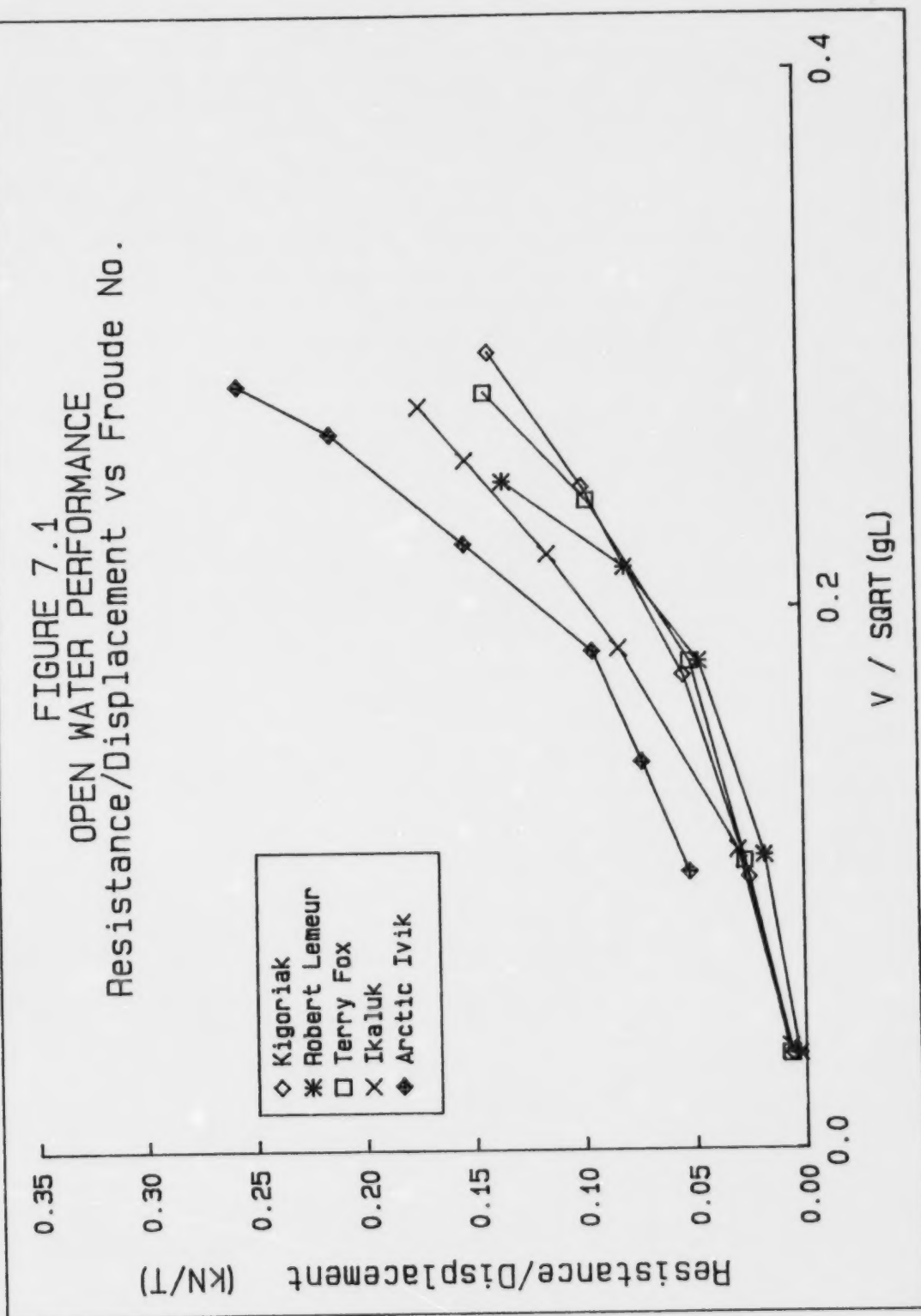
#### 7.4 Conclusions

The calm water specific resistance versus Froude Number curves for the vessels follow logical trends for vessels of the same general form including all Beafort Sea icebreakers, but different size and fullness.

Specific resistance increases with Froude number and block coefficient and decreases with vessel size. Reamers and wedges are expected to have a significant influence by increasing the resistance. There are insufficient data to show this directly, due to lack of data with ships without any such features, but it is judged that the reamers of the Kigoriak have a very similar influence on open water performance as the wedge of Terry Fox.

The data are specifically for contemporary chined icebreakers with a variety of special shapes, the data is not applicable for prediction of open water performance of fully developed "conventional" body icebreakers.

FIGURE 7.1  
OPEN WATER PERFORMANCE  
Resistance/Displacement vs Froude No.



2



## 8. RIDGE PERFORMANCE

### 8.1 Introduction

The performance of icebreakers in ridges can be assessed by the time required to penetrate a certain size ridge profile. This time is a function of the number of rams and the time per ram.

The number of rams for a given ridge profile is determined by the penetration per ram and the total length of the ridge profile. The penetration distance is a function of the resistance of the ship in the ridge and the available ship's energy.

The time per ram is composed of the following segments;

- acceleration, from start ahead to impact
- penetration, from impact to stopped
- extraction, from stopped to start of astern movement
- backing, from start of astern to stopped

The acceleration time is a function of the displacement of the ship and available ship's thrust and the resistance, which can be relatively small if approaching the ridge from open water or large if operating in a channel with a high concentration of thick ice.

The penetration time is a function of the available energy and the ship's resistance in the ridge. The resistance is a function of the shape of the ship and the properties of the ridge. In the limiting case where the ship is just able to maintain continuous ahead progress, the available thrust becomes a major factor.

The extraction time is a function of ship shape, the friction between the ship and the ice, including any influence of hull condition or coating and lubrication devices, the available astern thrust and the availability of other aids such as heeling or trimming tanks.

The backing time extends from the time the ship first moves astern to the time of the start of the forward acceleration segment. The backing time is a function of the available thrust, ship displacement, the resistance and the astern/ahead backing time. As for open water, the resistance will depend upon the ice concentration and the ship shape.

Three sets of ridge performance data are available for this study; the Kigoriak and the Robert Lemeur in first year ridges in the winter and the Kalvik in predominantly thick weak first year and old ice in the fall. As described in the



environmental section, the Kigoriak and Robert Lemeur data are comparable, but the Kalvik data are not, due to the different ice properties; primarily ice strength, friction and degree of consolidation.

In the following sections, the data sets are analysed to obtain information on the ridge resistance/penetration energy and the ramming cycle performance. The analysis is based on the original analysis carried out in the referenced data.

## **8.2. Ridge Resistance and Penetration Energy**

### **8.2.1. General**

A full presentation of the resistance and penetration energy in ridges has been given in (31,32,33). In this Section the relevant aspects are described for this project.

The energy it takes to penetrate a ridge is an important input into the operational efficiency of an icebreaker. Knowing the penetration energy, the minimum size of ridge where the icebreaker must start to ram can be determined. Ridge testing is normally performed in large ridge fields in order to establish the capability of the icebreaker in the most onerous conditions. It is then possible to determine the performance in intermediate and small ridges, by interpolating between the level ice performance and the performance in the large ridge field.

The most important measure of performance through ridged ice is the average speed. The speed will depend upon the following ice parameters:

- thickness of the level ice
- width and depth of the ridge profile
- degree of consolidation

Beside the performance in the approach channel both ahead and astern, the speed is also dependent upon the following ridge/ship interaction parameters:

- ramming required or not
- ship's power/displacement ratio
- Extraction capabilities (astern power and friction reduction)

The first major degradation in performance in ridged conditions is reached when the ship must resort to ramming. The ramming cycle takes so much time that the average speed drops considerably. The second major degradation in performance occurs when ridge becomes so large that the ship has difficulty in extraction. This is normally far beyond the first degradation limit.

### 8.2.2 Data Analysis and Conclusions

The ridge resistance in the original reports of the Kigoriak and the Robert Lemeur was determined by summing the estimated net thrust from the propulsion system and the mass force determined from the deceleration of the ship. The effective ship mass included 30 % for added mass. Both the deceleration and thrust forces have been averaged over the ram. The average speed after impact during the ram was taken as half the impact speed. As the deceleration during the ram was close to constant, this was a reasonable assumption. The only exception to this constant deceleration was a deceleration peak if the ice knife contacted the ice. This caused an increased resistance. The penetration energy was calculated from the ridge resistance and the distance of penetration.

Both the resistance and the energy were plotted against the ridge profile properties determined from on ice measurements. As shown in figures 8.1 and 8.2 the resistance was plotted against the average ridge thickness from sail to keel along the ship penetration line and the energy against the penetrated cross sectional area. The resistance has been divided into two components, the consolidated level ice resistance (level ice thickness plus 50 %) and the pure ridge resistance. The first one is in a major way breaking dominated, whereas the second one is mainly determined by the resistance to move the rubble mass away from the ships passage.

With one exception, the original analyses for the Robert Lemeur and the Kigoriak have been performed in a comparable fashion. The degree of consolidation for the ridges of the Robert Lemeur tests was not analysed. This has been done in the present study and the results replotted.

The rams of the Kalvik were analysed in a similar fashion to those of the Kigoriak and the Robert Lemeur.

From figure 8.1 the resistance of the Robert Lemeur in the unconsolidated portion of the ridge is less than that of the Kigoriak. The difference is in direct proportion to the size of the hole that each ship makes. The cross sectional area of the Kigoriak is approximately  $150 \text{ m}^2$  and the Robert Lemeur is  $105 \text{ m}^2$ , or about 70% of that of the Kigoriak. The areas are based on the widest part of the ship.

Similarly the energy to penetrate the ridge, excluding the consolidated portion is in proportion to the cross sectional area of the ship.

This indicates that the shape of the hull may not be very important in determining the average penetration resistance in ridges. This statement is limited to the family of hull shapes that push ice down rather than sideways. For conventional hull

shapes that push ice aside, particularly at the shoulders, a comparable analysis would need to be performed to determine trends.

For the Robert Lemeur and the Kigoriak, the specific energy per unit volume of rubble removed is  $33 \text{ kJ/m}^3$ . The average penetration energy including the consolidated portion is  $35 \text{ kJ/m}^3$  for the Kigoriak and  $21 \text{ kJ/m}^3$  for the Robert Lemeur. The difference between the two ships is greater than the difference in the cross sectional areas by about 15%. This is thought to be due to the lower hull resistance of the Robert Lemeur in breaking level ice ie. the consolidated portion of the ridge.

The penetration energy for the Kalvik is  $47 \text{ kJ/m}^3$ . This number should not be compared with the results of the other ships as it represents the performance in consolidated ice only. In addition as the tests were conducted in the fall, the ice strength and the friction factor were different due to the warmer conditions.

### 8.3 Ramming Cycle Performance

#### 8.3.1 General

Ramming cycle data is available for the Kigoriak, the Robert Lemeur and the Kalvik. As the Robert Lemeur and the Kigoriak were tested in similar conditions, the two data sets can be compared. The Kalvik was tested in different conditions as described in the section on the environment and should not be compared with the data from the other ships.

#### 8.3.2 Data Analysis and Conclusions

The results from the Kigoriak and the Robert Lemeur are as analysed originally by Canmar, with further analysis of the Kigoriak rams to determine the dependency of impact speed and the ram cycle time on the thickness of the consolidated portion of the ridge (shown in figures 8.3 and 8.4 respectively).

For the Kalvik, rams were selected that were close to full power. These rams were further analysed to remove any rams with penetration distances that were excessive, as these were judged to be too close to continuous ahead performance. Even with these rams removed the penetration distances were much longer than those of the Kigoriak and the Robert Lemeur, indicating that the Kalvik rams can not be considered representative for severe ridge ramming. The Kalvik selected rams are tabulated in Appendix D.

Table 8.1 summarizes the average times for the ramming cycle components, the average impact speeds and the average penetration distances for each of the ships.

Comparison of the Kigoriak and the Robert Lemeur data leads to the following observations:

1) Although the two ships have equivalent acceleration times, the impact speeds are different. As the Kigoriak has a greater power/displacement ratio, she would be expected to have a greater terminal velocity for equal ice thicknesses. As the Kigoriak tests were conducted later in the season the level ice thicknesses and the degree of consolidation were greater, and hence the resistance in the channel was greater. This is supported by figure 8.4 which shows a decrease in the ramming speed achievable with increasing ridge consolidation ( and the associated thicker level ice).

2) The penetration distances and times are greater for the Robert Lemeur. These are primarily due to the greater impact speeds and the lesser ice conditions of the Robert Lemeur, but are also influenced by the shallower stem angle and the location of the ice knife on the Robert Lemeur.

3) The greater extraction times of the Robert Lemeur are primarily due to the shallower stem angles and the smaller power/ displacement ratio.

4) The greater backing time of the Robert Lemeur is due to the poorer astern performance. This is even more striking when the difference in the environmental conditions is considered.

Figure 8.4 shows that the ram cycle time during the test series was independent of the thickness of consolidation. In some measure, it is operator dependent as the operator will choose the distance (and hence time) that the ship backs depending on the environmental conditions and the ship performance. This distance will determine the acceleration distance and the impact speed. The present data reflects the operation of one master. As shown on figure 8.3, the ram impact speeds are not independent of the degree of consolidation.

Although not specifically addressed in the table, another factor in the ramming cycle time is the time spent clearing the blocked nozzle(s). This is discussed in the section on propeller/ice interaction.

The relatively short times for acceleration and backing for the Kalvik are primarily indicative of the easier approach ice conditions. The longer extraction times are due to the greater friction forces due to the depth of immersion of the hull in the ice in the longer penetration rams.



FIGURE 8.1  
PENETRATION RESISTANCE  
In First Year Ridges  
Winter Conditions

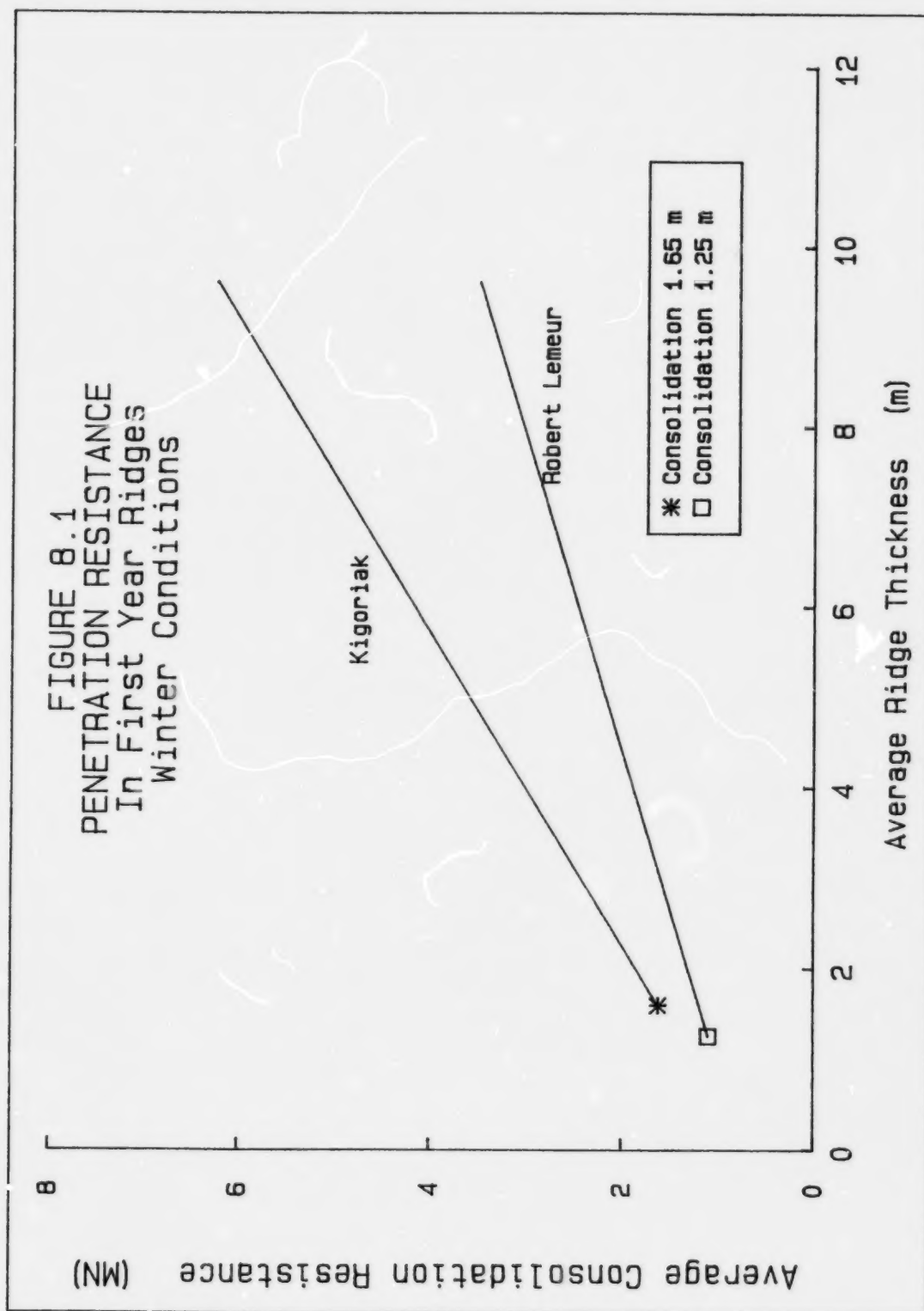




FIGURE 8.2  
ENERGY OF PENETRATION  
In First Year Ridges  
Winter Conditions

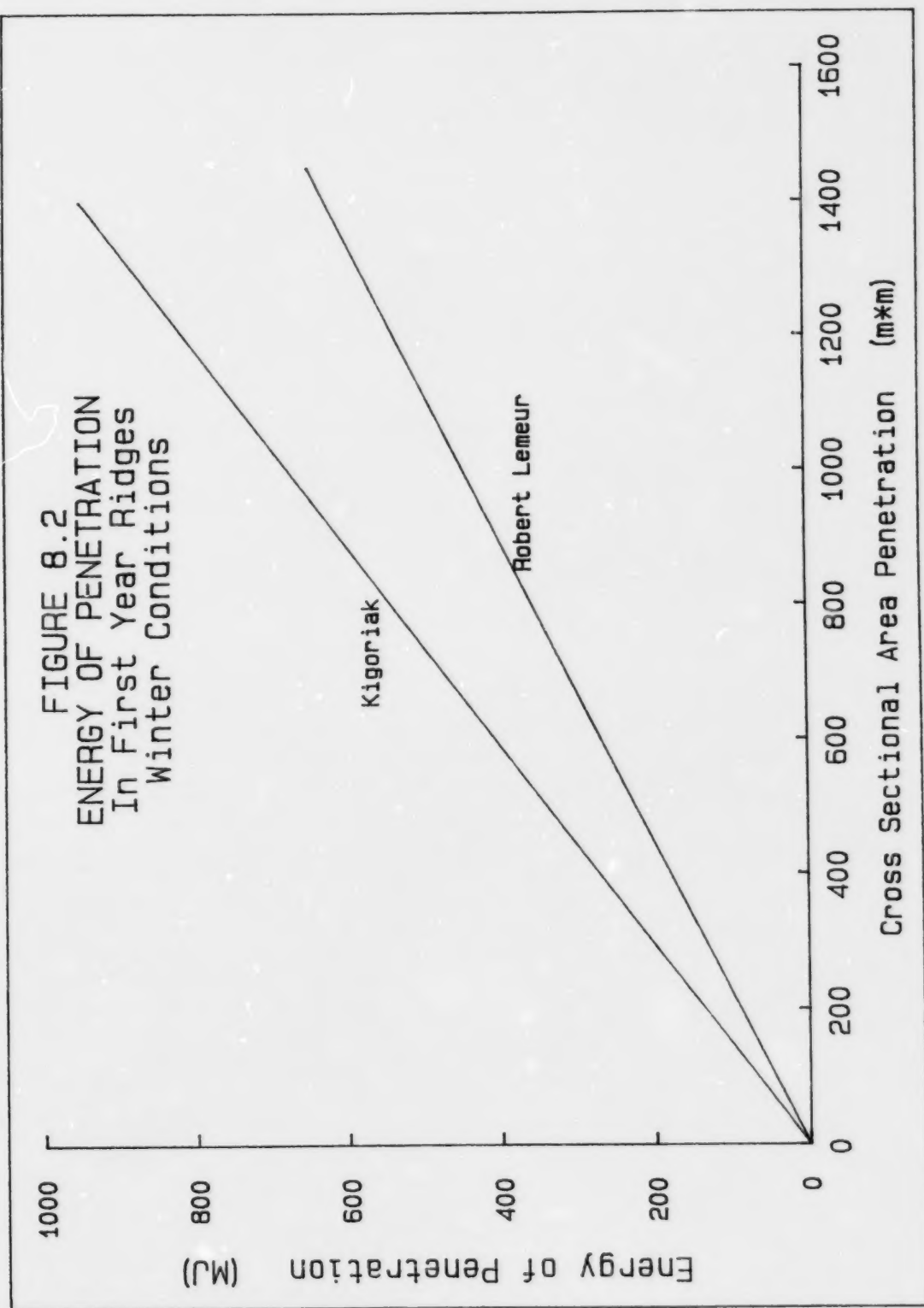


FIGURE 8.3  
INFLUENCE OF ICE THICKNESS ON  
IMPACT SPEED IN RIDGES

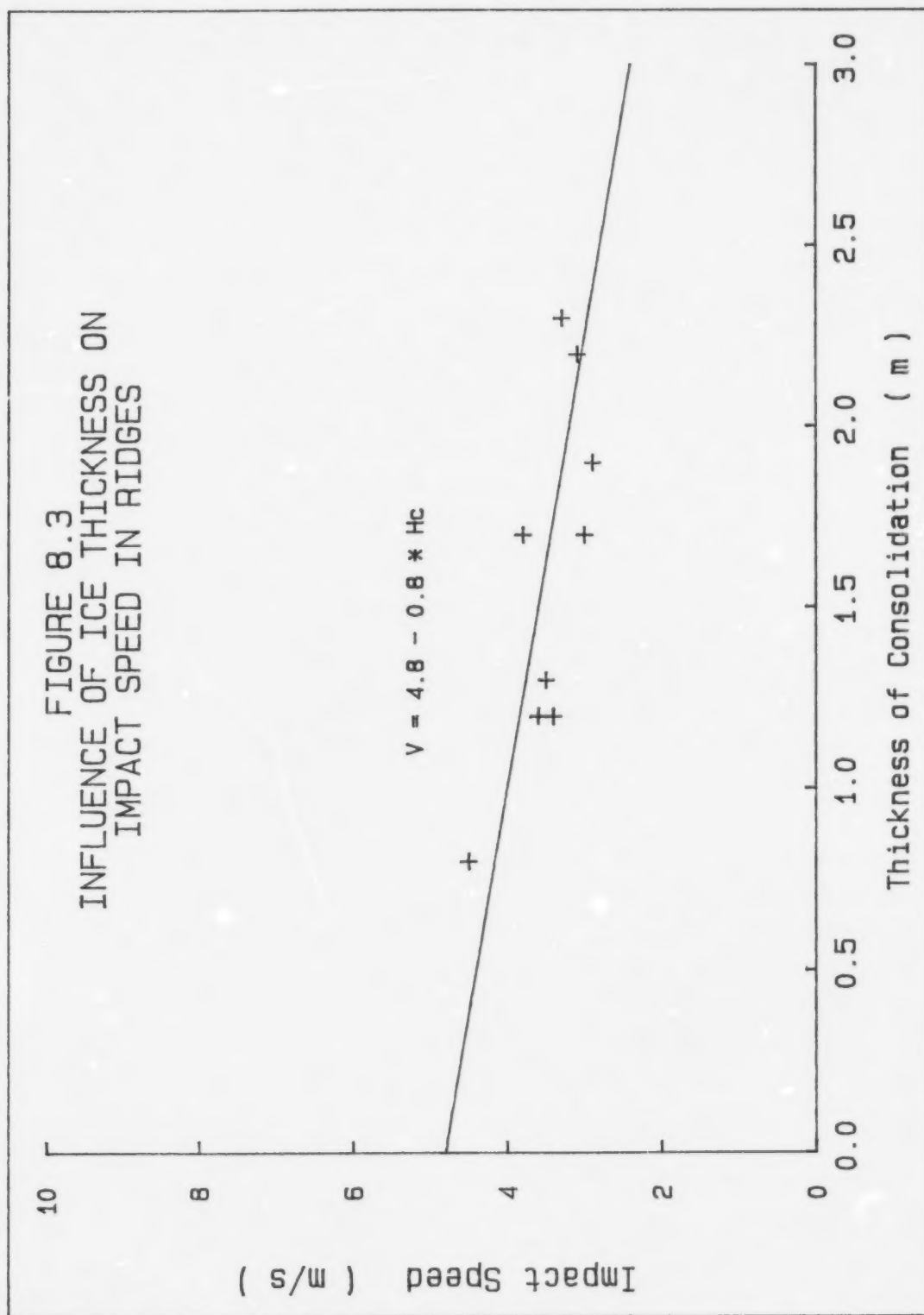


FIGURE 8.4  
INFLUENCE OF ICE THICKNESS  
ON RIDGE RAMMING CYCLE

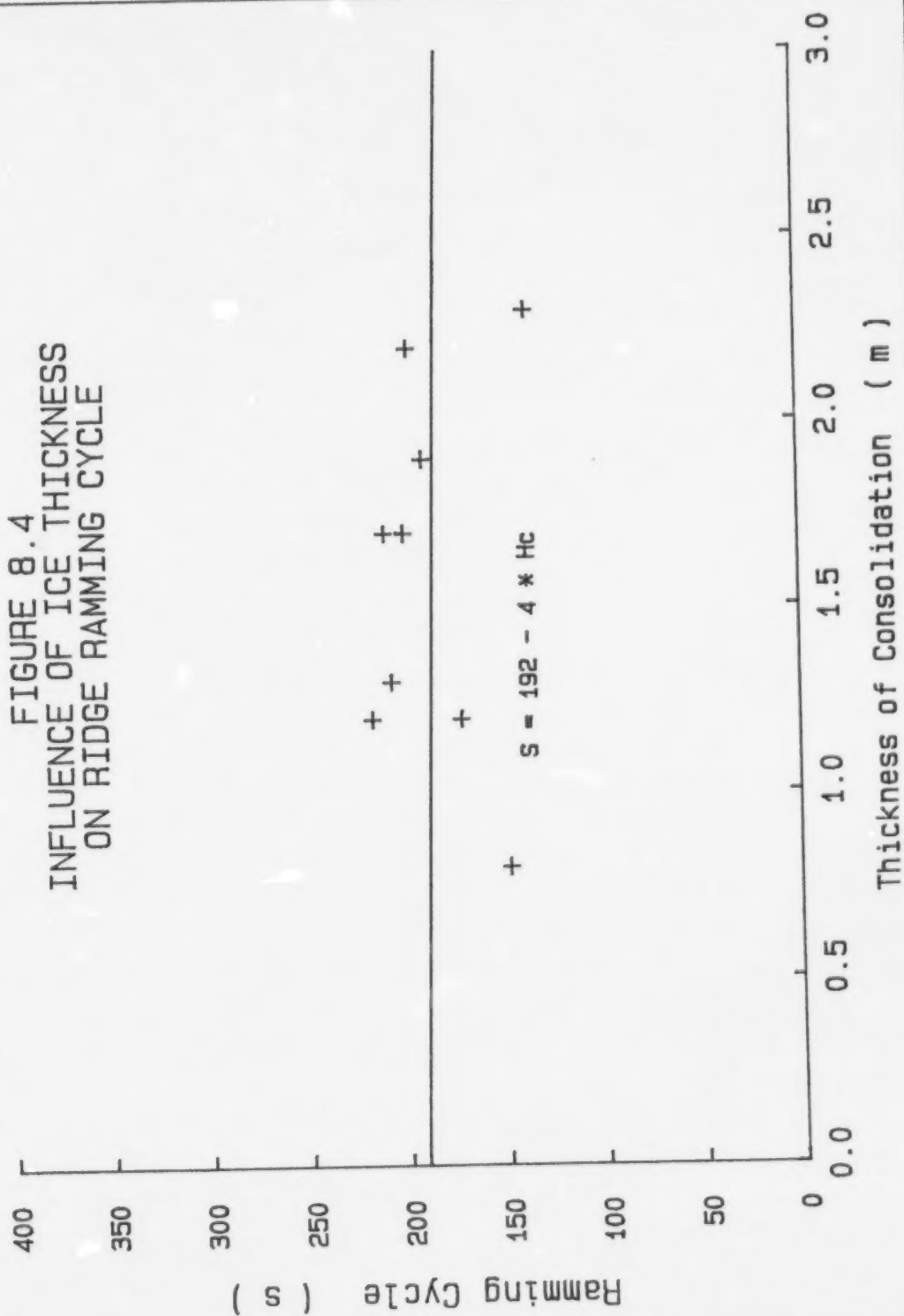


TABLE 8.1

## RAM CYCLE PARAMETERS

|                       | KIGORIAK | ROBERT LEMEUR | KALVIK |
|-----------------------|----------|---------------|--------|
| ACCELERATION TIME (S) | 67       | 66            | 35     |
| SPEED OF IMPACT (M/S) | 2.6      | 3.5           | 3.8    |
| PENETRATION DIST. (M) | 13.3     | 17.6          | 56.9   |
| PENETRATION TIME (S)  | 6.0      | 12.0          | 33.0   |
| EXTRACTION TIME (S)   | app. 0   | 15.0          | 44.0   |
| REVERSAL TIME (S)     | 103      | 145           | 83     |
| TOTAL CYCLE TIME (S)  | 195      | 235           | 194    |

## 9. TRANSIT PERFORMANCE

### 9.1 General

A transit is a voyage from point A to point B in a regime of mixed ice conditions. The performance of the ship is assessed by the average speed over the distance covered.

The ice regime will include:

- level ice
- ridges
- rubble fields
- open water (including leads)

If significant wind or currents are present the ice may be pressured.

The average speed that the ship can attain in the mixed regime will generally be less than the speed possible over the route if only level ice were encountered. The factors that will increase the average speed are the amount of:

- open water
- freshly broken channels

The factors that will decrease the average speed are:

- ridges
- rubble
- pressure
- high friction conditions such as significant snow cover or mushy ice

The distance covered between A and B may not be the shortest distance as an alternate longer route may have less onerous conditions, ie less ridging and rubble, more leads, less pressure etc.. Finding this alternative route requires reconnaissance which may take the form of observation from the bridge, helicopter flights, imagery from SLAR overflights etc.. The ability to take advantage of the easier route may in the short term depend upon the vessel's manoeuvrability.

In the present data set, the following transit information exists:

Kigoriak

- a voyage from Summers Harbour to McKinley Bay in January 1980 covering a total distance of 291 km.



- breakout in June 1980 from McKinley Bay covering a distance of 45.0 kilometers.

#### Terry Fox

- transit through McKenzie Bay in January 1984 covering a total distance of 16.8 km.

#### Arctic Ivik

- two supply voyages from October 30 to November 3 1985 between Esso Rig 3 and Tuktoyaktuk.

The environmental data associated with these transits is not directly comparable because of the different levels of effort in collecting the data and the different criteria in categorizing the data. Direct comparison of the results should not be made, although the general trends can be compared.

### 9.2 Data Analysis of Results

The average transit speeds for the Kigoriak in January and June have been plotted against the month on figure 9.1. To put these speeds into context the speed attainable in the thickness of level ice at the time of the transit has been plotted. In addition the growth of the level ice thickness over the season has been plotted. As the number of ridges rammed has a dramatic effect on the average speed this has also been plotted based on the data for the January and June transits.

The results show the large reduction in average transit speed as the ice thickness increases and the number of ridges that must be rammed increases. In January the average transit speed is 31% of the level ice speed, whereas in June the average speed is only 8%.

The transit of the Arctic Ivik occurred in the early winter season conditions with thinner ice and little ridging. She was able to maintain an average speed of 40% of the level ice thickness speed. Due to the smaller size of the Arctic Ivik the results should not be compared directly with the results of the larger ships. The results do show that relatively high transit speeds can be achieved with small ships in light ice conditions (ie about 50% of level ice capabilities).

Results have been plotted for two of the longer segments of the transit of the Terry Fox. The upper point has a concentration of rubble and ridges of 30% (ie 70% level ice) and the ship is able to maintain 53% of the level ice speed. The lower point has a concentration of 50% of rubble and ridges and the average speed is only 26% of the level ice speed. Again the speed drops significantly with the increase of ridging.

Figure 9.2 taken from the Canmar analysis of the January 1980 transit, shows how the average speed for segments of the voyage drops for an increased number of ridges per nautical mile. At 30 ridges per mile the average speed has dropped to about 10% of the 0.90 m level ice speed of 3.9 m/s. Although not shown on the plot the report shows that the average speed varies from a high of 8.03 m/s in a lead to a low of 0.15 m/s in a heavily ridged segment.

An analysis (see Appendix D) of the five segments of the Terry Fox transit has been plotted on the above figure. Because of the different manner in which the ridges have been analysed, the results should not be compared directly. However the results do show a similar trend with a large reduction in average speed with increasing frequency of ridges.

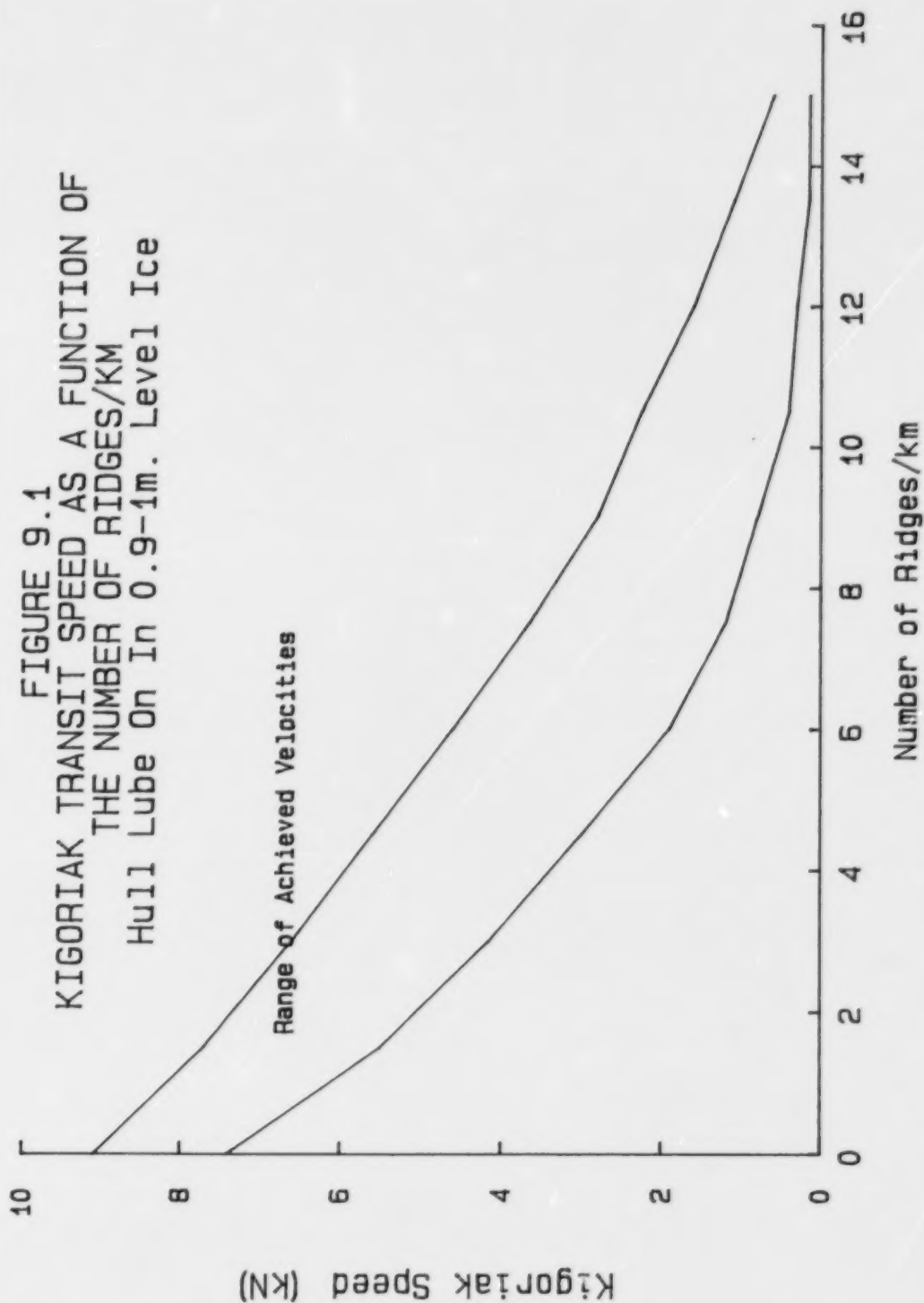
### 9.3 Conclusions

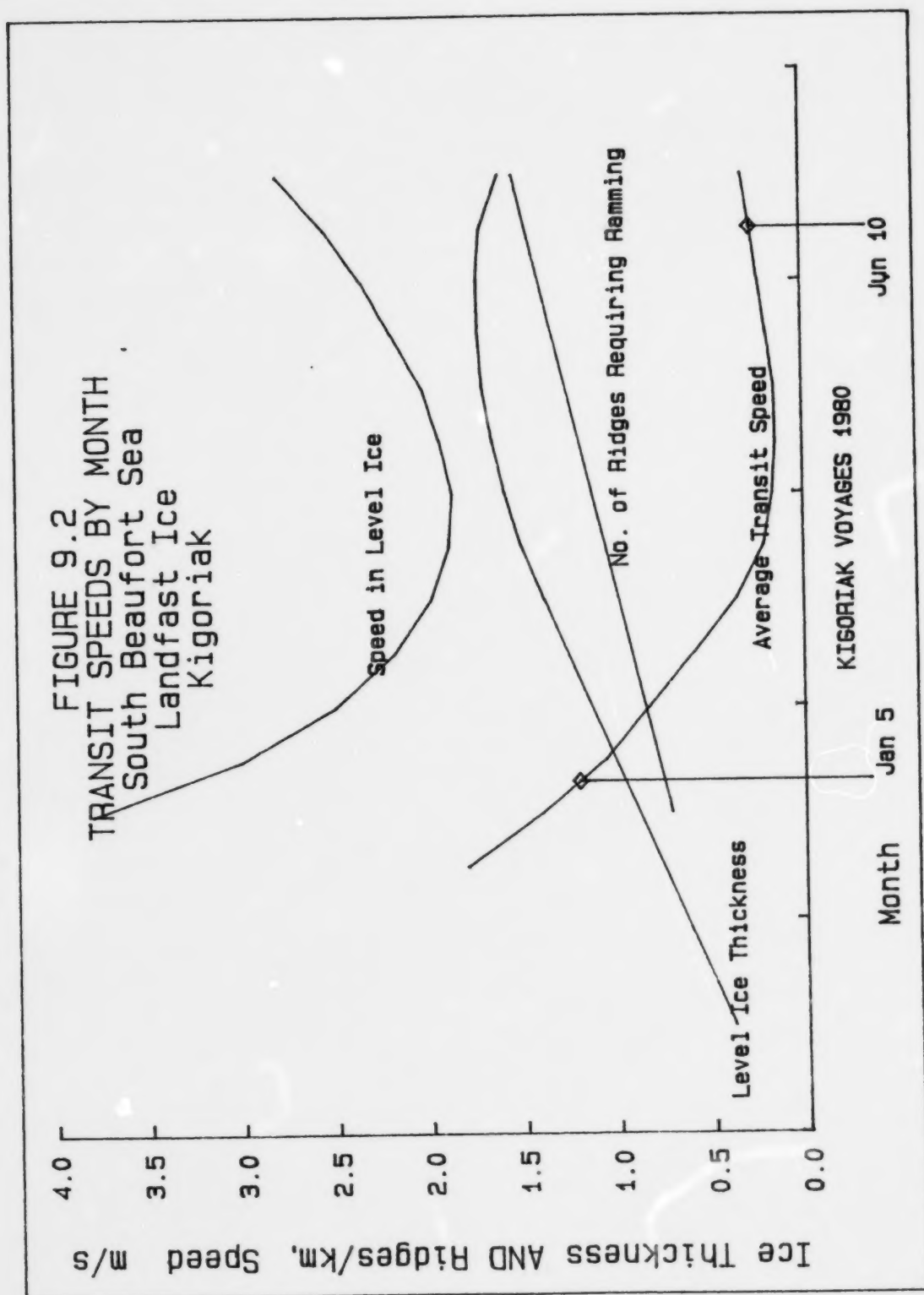
1) The ability to operate efficiently in ridges (ie fast ram cycle times and long penetrations) will determine the effective average transit speed in heavily ridged conditions.

2) The average transit speed can be expressed as a percentage of the level ice speed allowing for the concentration of ridges.

3) For effective transit in ridged conditions, the speed in the level ice to be encountered should be well in excess of minimum requirements. This will ensure a reserve for the ridges for fast impact speeds and hence effective penetration per ram. As an example, current thinking would specify a speed of 1.5 m/s as a design speed for the maximum level ice to be encountered. If the maximum level ice to be encountered were 1.0 m then designing a ship for this speed that is intended for a transit role would result in a ship with an extremely low average transit speed. Based on the Kigoriak June results the speed would be 0.12 m/s. Baltic experience has shown that the design speed for level ice should be about 4.0 m/s if the vessel is to be effective in transit.

FIGURE 9.1  
KIGORIAK TRANSIT SPEED AS A FUNCTION OF  
THE NUMBER OF RIDGES/KM  
Hull Lube On In 0.9-1m. Level Ice









## 10 PROPELLER ICE INTERACTION

### 10.1 General

Propeller ice interaction includes the following phenomena:

- 1) Single impacts by small pieces of ice that are able to pass through the propeller blade plane hitting one blade only.
- 2) Multiple impacts (milling) on consecutive blades caused by a piece of ice that is too large to pass through the blade plane without being broken apart.
- 3) Blockage of the nozzle caused by a piece of ice that is too large to enter the nozzle.

The occurrence of these phenomena can be characterised by the following parameters:

- frequency
- duration
- severity
- operational conditions in which they occur

Frequency is defined as the number of interactions in a given time period. Duration is defined as the length of time of an individual interaction or the percentage of time in which interactions occur. Severity is defined as the increase over mean open water values of torque, thrust, propeller blade stress etc..

The operational conditions are defined as modes of operation such as astern, ahead, manoeuvring etc., the operating condition of the ship such as draft, trim, ice clearing features on or off etc. or the environmental conditions such as level ice, ridges, broken channels etc..

This section will only deal with the preceding facets of propeller/ice interaction. Although other aspects of propeller/ice interaction such as the effects on the propulsion and control systems and the reduction in effective thrust are important in the overall operation of the ship, the data set available to this study did not include this information.

The most comprehensive data set for propeller/ice interaction is from the winter 1980 tests of the Kigoriak. The discussion in this section will be limited to this data. Data for other ships is discussed in Appendix D.

## 10.2 Data Analysis

Figure 10.1 shows the time spent by the Kigoriak in propeller/ice interactions of all types as a percentage of total operating time. In ahead motion, interactions are insignificant until an ice thickness of 1.5 metres is reached. Astern, the interactions are about 45% of the time at 1.0 metres ice thickness rising to about 65% at 1.5 metres thickness. The time of interaction of the Captain's Manoeuvre lies between the ahead and astern times due to the astern components of the manoeuvre.

In ramming trials on the Kigoriak, blockage had a dramatic influence on the ramming cycle time. As shown on figure 10.2, the expected ram cycle time was 190 to 200 seconds. For the 36 rams in which clearing was required, an average clearing time of 128 seconds with a standard deviation of 103 seconds was required. (For the 128 rams in the data set this averaged 44 seconds per ram.) For all rams, the expected time in clearing was 15% to 20% of the ram cycle time. The blockage occurred primarily when the operator applied full ahead power to accelerate the ship in a heavily clogged channel at speeds less than 1.5 metres/second. The blockage could be considerably reduced if the operator slowly applied power until this speed was reached and then applied full power.

The transit of the Kigoriak in January 1980 (see section 9.0), covered 291 km in 66 hours for an average speed of 4.4 km/hr. A total of 734 rams were needed to penetrate the 215 ridges that required ramming. Assuming an average of 44 seconds per ram to clear blockage, a total time of almost 9 hours or 14% was spent in clearing blockage. If no blockage had been present the average speed would have been 5.1 km/hr.

## 10.3 Conclusions

1) In ahead level ice the Kigoriak's hull form is very effective in keeping ice out of the propeller in ice thicknesses up to 1.50 metres. The centreline propeller and the rise of floor are the major contributing factors. Astern the propeller unprotected by the hull form ingests significant quantities of ice.

2) In general the amount of propeller/ice interaction goes up with increased ice thickness.

3) Blockage occurs on all the nozzled ships. It can erode the performance significantly in ridges and hence in transits in ridged conditions, due to the time it takes to clear the nozzle.

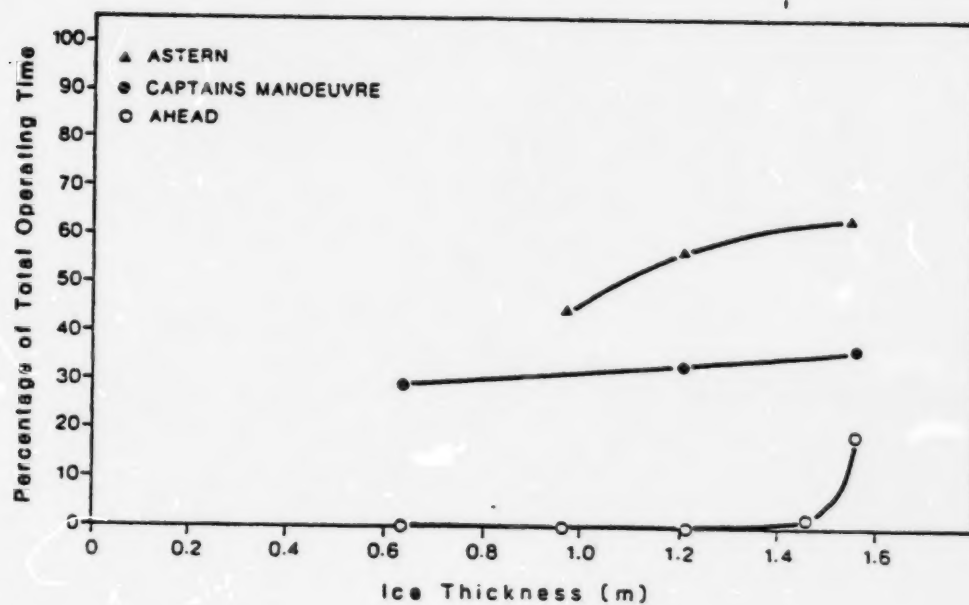


FIGURE 10.1  
KIGORIAK: Time Spent in Propeller Ice Interaction

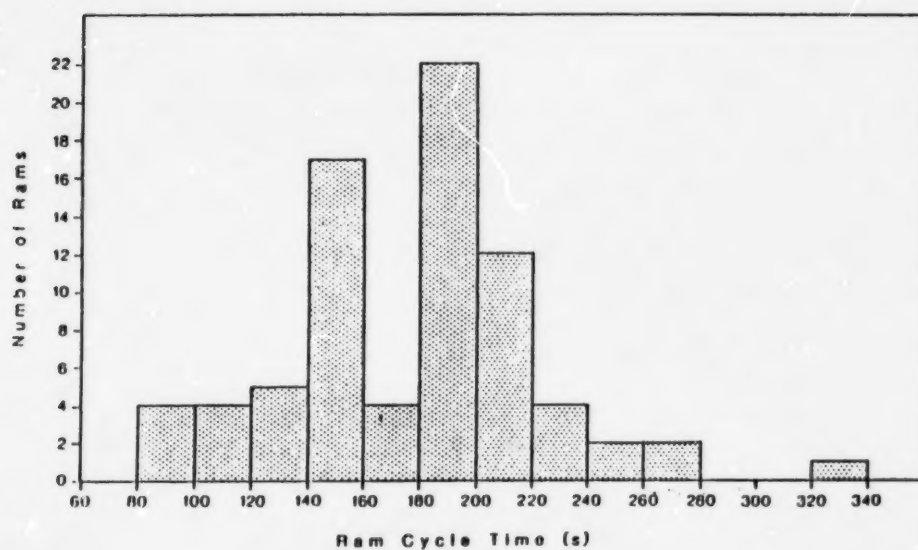


FIGURE 10.2  
KIGORIAK: Total Ram Cycle Time Distribution

## 11. PERFORMANCE ESTIMATION MODELS

### 11.1. General

Performance estimation models are developed in the form of empirical mathematical formulae which provide a good fit to the analyzed data and incorporate relationships demonstrated by the full scale data. The performance components for which the estimation models are developed are:

- Level ice performance ahead
- Ridge performance
- Transit performance
- Open water performance
- Propulsion performance (open water only)
- Turning performance

The models include parametric influences from this project as well as from previously established relationships which can be supported by the data available to this project, APPENDICES A, D.

For any one performance estimation model the number of parameters involved is inevitably limited by the range of variables and volume of full scale data on which the models are based. In some cases, other environmental or design parameters might be judged to have an important influence upon performance but this is not detected or supportable by the particular data set. In these cases, the possible additional factors are listed without speculating on their influence beyond what the full scale data can support.

### 11.2. Level ice performance model

#### 11.2.1. General

The model calculates the ice resistance of a ship ahead in a range of level ice conditions covered by the full scale data. Combining this resistance model with the propulsion model, ship speed can also be calculated.

The basic model for ahead icebreaking resistance incorporates the following input parameters:

Beam  
Buttock angle, average over full width( or length) of bow  
Opening angle of frames, flare angle, average over bow  
Ice thickness (incorporating snow as well)  
Ship speed



### 11.2.2. Mathematical model

The mathematical model predicts the ice resistance of a vessel with a bow shape expressed by average buttock and flare angles.

The mathematical formulation is based on the full scale data and built in the following manner:

1. The basic resistance formula is derived from the full scale data in this report for a ship using a well established format:

$$R_{ice} = C_1 * B * H_1^{C_2}$$

where  $R_{ice}$  = Level ice resistance (MN)

$B$  = Ship beam (m)

$H_1$  = level ice thickness (m)

$C_1, C_2$  = coefficients depending on ship geometry and speed

The conditions for this are in this project: Winter Inertia coating and no hull lubrication devices.

2. The actual equation for a reference ship with a buttock angle of 15 degrees, flare angle of 68 degrees, and a beam of 19 meters is given. The thickness exponent applies for ice thicknesses of below 0.9 metres and a speed of 1 m/s.

$$R_1 = 0.43 * H_1^{1.45} \quad (\text{MN})$$

3. The influence of the bow shape is based on regression of full scale data in this report. The average buttock angles and the average flare angles of the frames over the bow region are used. The influence of the two angles can not be determined in a single step due to limited amount of full scale data range. Thus the model is built by first assuming a predetermined influence of the buttock angle based on general past experience and then calculating the influence of the flare angle, after the influence of the buttock angle is taken into account. The final model is selected based on comparisons on the different relative influences of buttock angles and flare angles on the resistance, in (D).

The influence of buttock angles is established for the speed range of 1 - 3 m/s as:

$$R = R_1 * [1 + 0.0054(\varphi - 15)^2]$$

where  $R$  = level ice resistance of a ship (MN)

$\varphi$  = average buttock angle over the bow

$R_1$  = resistance at  $\varphi = 15^\circ$

The influence of the flare angle is then:

$$R = R_1 * [1 + 0.00088 (\beta - 68)^2]$$

where  $\beta$  = average flare angle over the bow

$R_1$  = resistance for  $\beta = 68^\circ$

These influences are shown in Figures 11.2.1 and 11.2.2.

4. The influence of speed is taken from regression of full scale data in this report. There is no true uniformity in this but a representative presentation excluding the Robert Lemeur in the vicinity of 0.9 meter of ice thickness is:

$$R = R_1 * (1 + 0.28 * (v - 1))$$

where  $v$  = ship speed (m/s)

$R_1$  = resistance at  $v = 1$  m/s

5. The influence of hull lubrication or winter versus spring has not been incorporated reasons being:

The influence of the hull lubrication of the Kigoriak is considered specifically only applicable for the type and shape of hull as the Kigoriak has.

The definition of what is spring/fall ice condition is not clear, and to avoid any confusion or misuse of a mathematical model like this, it is at this stage left out.

The total formula for level ice resistance is built out of the above components:

$$R_1 = 0.43 * H^{1.45} * B * [1 + 0.0054 * (\varphi - 15)^2] * \\ * [1 + 0.00088 * (\beta - 68)^2] * [1 + 0.28 * (v - 1)]$$

Figure 11.2.3. shows the resistance prediction using the above established mathematical dependencies for the reference ship, varying the ice thickness and speed for winter ice with snow and no hull lubrication.

It has been shown in Appendix D how the selection of the exponents and factors for the influence of them has been achieved. In principle the influence of the buttock angles is first established based on basic knowledge of the icebreaker resistance as a function of the buttock angle. Then the resistances are all corrected to one standard buttock angle value and the influence of the flare angle is established.

### 11.2.3. Discussion

It is noted from Figure 11.2.2., where the mathematical model results are presented against the full scale data that the influence of the flare angle appears to be much too large. For example the resistance appears to increase by about 30 percent when the flare angle changes from 57 degrees to 47 degrees.

Possible reasons for the shown exaggerated dependency of resistance on the flare angle are from two sources:

1. The inability on the data analysis to make exhaustive corrections for variation of environmental conditions and propulsion performance due to a lack of relevant information, lack of established methodology and limited scope of the project. These aspects are:

- The ice conditions have not been identical for the tests. There is an indication that the ice has been stronger for the tests of the Terry Fox and Ikaluk than for other Beaufort Sea Icebreakers, and on the other hand there is a clear indication of the ice having been weaker in the Baltic for the tests of Max Waldeck. These have not been corrected for. The maximum influence from these is estimated at a maximum 10 percent reduction of the resistance of the Terry Fox and Ikaluk. The increase at maximum for the Max Waldeck could be less than that.
- The thrust for all ships is taken similar for all powers and speeds. There is a reason to believe that the thrust of the smaller propellers could be lower than in this study. Also there is evidence that the thrust of Robert Lemeur would likely be lower at higher speeds than the estimation equation gives. This is the consequence to the fact that the propulsion island eliminates the favourable wake from propellers.

2. The influence of such ship design parameters and features which it has not been possible to detect based on the full scale data analysis and are therefore not included in the model. In particular their collective effect, if similar for example to that of flare angle, would mask their presence and be called a flare angle influence.

- The ships represent three different concepts, the Kigoriak and Robert Lemeur have rounded bows and reamers, the Terry Fox, Ikaluk and Ivik represent reamerless chined design, and the Max Waldeck represents a shearing principle icebreaker with an equivalent reamer. These differences are not accounted for in this project. The influence of the reamers is not known. They are expected to reduce the midbody friction.

tion. Thus the resistance for the purpose of evaluation of the influence of hull shape alone would have to either increase the resistance for the ships with reamers or correspondingly decrease it for the ships without reamers.

- The ships have various designs of wedges under the bows of them. These have not been accounted for in this project either. The influence of wedges should be eliminated first before being able to assess the influence of the hull shape alone. the resistance for the wedges of the Terry Fox , Ivik and Ikaluk should be subtracted for this comparison. However, there is no known way of doing this with any confidence.
- The Length of the ship influences the friction resistance along the midbody. All the Beaufort Sea Ice-breakers are so close to the same length that the influence of length is virtually eliminated for these approximately similarly proportioned ships.
- Draft influences resistance in a complicated way. It is tied to the friction resistance as well as to the ship size as well as to the influence of any wedges. Its influence is not normally considered nearly as important as the influence of the main parameters which are incorporated to the model. Also its influence has been contradictory in past work.
- Midbody side slope potentially influences accumulation of ice around midship and thus the friction resistance.
- Ship size can influence the amount of energy consumed in ship motions due to ice breakage in thick ice where the impact of ship with the ice edge does not break the cusps, but ship needs to climb onto the ice before this breakage occurs.

It is clear however that the trends shown in Figures 11.2.1. - 11.2.2. are indicative of the influence of the buttock angles and the flare angles on the resistance but due to the above listed differences between the ships they are exaggerated.

### 11.3. Ridge performance

#### 11.3.1. General

The full scale data in ridges comes from the Kigoriak and Robert Lemeur. The tests have been performed in midwinter ridges in the Beaufort Sea. Accordingly the model is developed



to apply to that condition only, and is calibrated to this data.

There are two parts to the ridge performance modeling. First the resistance of the ship in the ridges, secondly the ramming cycle performance. The ramming cycle performance ideally should incorporate influences such as the extraction, and influence of the propeller ice interaction on the ramming performance, and the basic acceleration characteristics of the ship varying with ice thickness. However, a simpler approach is taken here where these influences are not built into the model. Such influences can be assessed separately with a better confidence on a case by case basis.

Based on the full scale data an accurate model can be developed for the ridge resistance. The ramming cycle performance could not be meaningfully modeled based on the full scale data calibration. This is due to the fact that in the case of the ramming cycle data for three ships which exist, the ramming cycle time that actually is resulting is about the same despite of important differences in the ships from which the data comes from. Also, the channel condition for ramming which influence the ramming cycle to an important degree, are not recorded in the full scale data for proper evaluation of the ramming performance. It is concluded that the practical ramming cycle is actually determined for the ships with data on ramming, by the operators general preference. The ramming cycle is close to being constant, as seen in Section 8, and the variable is then the impact speed depending on the ice conditions, as also seen in Section 8.

The main mathematical model calculates the ridge resistance. An approach used in the past (31,32,33), is adopted here. This basically calculates the following components of the ridge resistance:

- level ice resistance in the consolidated thickness of approximately level ice ( solid ice ) within the ridge.
- pure ridge resistance, due to the unconsolidated ice blocks in the keel and in the sail of the ridge.

The ridge penetration speed calculation model takes the full scale data based parameters for the ramming cycle and translates them to energy available per ram for a ship. The speed then determines the number of rams required to overcome the total energy for penetration of the ridge.



### 11.3.2. Parameters

The ridge resistance model incorporates the following parameters:

- Beam
- Draft
- Ridge thickness
- Consolidated ice thickness

The ramming cycle model uses constant ramming cycle time and changes the ramming impact speed as a function of the local surrounding ice thickness where the ridge is, according to full scale data, in Section 8. The parameters included are:

- Impact speed
- Influence of ice thickness on impact speed
- Influence of long ridge on impact speed
- Ramming cycle

### 11.3.3. Mathematical Models

The pure ridge resistance is expressed as shown in Reference (30). This is in the format:

$$R_r = C * B * H * T$$

where  $R_r$  = pure ridge resistance (MN)  
B = ship beam (m)  
H = ridge thickness, average (m)  
T = ship draft (m)  
C = coefficient

On top of this, the level ice resistance in the consolidated thickness of ice within the ridge is added. The Beaufort Sea data for Arctic ridges in winter suggests that the thickness of the consolidated ice within a ridge is 50% greater than that of the surrounding ice. Thus, the resistance in this consolidation is taken as the level ice resistance in 1.5 times the level ice thickness outside of the ridge. This applies to ridges in the Arctic which are formed, as a rough rule, at least a week before the ship passage.

The pure ridge resistance ( without the consolidation portion ) is given by an equation:

$$R_r = 3.7 * B * H * T$$

This equation applies both for the Kigoriak and Robert Lemeur in the Beaufort Sea ridges by reproducing their actual analyzed ridge resistance (D). The prediction for the Kigo-

riak and Robert Lemeur is the same as shown as their full scale data line in Figure 8.1.

The consolidation portion of the resistance for the two ships is the level ice resistance in the thickness of ice which forms the consolidation. This can be seen in Figure 8.1.

The equation for the total energy required to penetrate a ridge is:

$$E_r = 3.7 * L_p * B * T * H_r + \\ + L_p * 0.43 * H_{lc}^{1.45} * B * [1 + 0.0054 * (\psi - 15)^2] * \\ * [1 + 0.00088 * (\beta - 68)^2] * [1 + 0.28 * (v - 1)]$$

where  $E_r$  = Ridge penetration energy (MNm)  
 $L_p$  = length of total penetration (m)  
 $H_r$  = average ridge thickness (m)  
 $H_{lc}$  = total consolidation thickness (m)  
 $\psi$  = average buttock angle  
 $\beta$  = average flare angle  
 $v$  = average speed during ram (m/s)

In this equation the first line is the pure ridge energy, the second line the energy related to the level breaking of the consolidated layer as influenced by the buttock angle, and the third line is the influence of flare angle and speed on that energy. The average speed should be taken for this equation as 2 m/s for a general ridge ramming case, which represents half the expected impact speed.

The ramming cycle which turns out to be nearly an operator selected time parameter is given as input into the ramming model. The outcoming impact speed decreases then with increasing ice thickness. It is shown in Figure 8.3. how the impact speed is influenced and in Figure 8.4. how the ramming cycle is not influenced by the ice thickness. These come from the Kigoriak full scale data (D). The influence of ramming into ridges longer in the direction of ship travel is represented by another decrease of impact speed in the ridge, due to heavier channel to reach the unbroken section of the ridge profile. This is expressed by equation (D):

$$V_{\text{impact}} = V_1 - 0.16 * N$$

Where  $V_{\text{impact}}$  = actual impact speed on N;th ram  
 $V_1$  = impact speed on first ram on a ridge  
 $N$  = number of a ram into a ridge

The actual ramming cycle is taken at 200 seconds (figure 8.4) . The actual dependency of the impact speed on the ice thickness follows the line, Figure 8.3:

$$V_1 = 4.8 - 0.8 * H_{1C} \text{ (m/s)}$$

where  $H_{1C}$  = thickness of consolidated ice =  $1.5 * H_1$  (m)  
 $H_1$  = level ice thickness (m)

The extent of penetration of ridge depends on the energy required to penetrate the ridge and the input energy of the ship. When applying the ridge ramming model only to ridges thick enough to require a considerable amount of energy the propulsion energy can be left out of the comparison. The energy to penetrate ridges is given by the energy to penetrate the consolidated thickness of level ice plus the unconsolidated ridge portion. The unconsolidated ridge portion energy is given as in Figure 8.2. The energy to penetrate the level ice is assumed for a distance of 50 meters for the level ice. This gives the practical penetration speed for the Kigoriak and the Robert Lemeur as shown in Figure 11.3.1.

#### 11.3.4. Discussion

The ridge resistance model on page 11.7 has been applied to several ships before the Beaufort Sea application here. It seems to be a reasonably accurate way of expressing the resistance of the unconsolidated portion of the first year ridges. There has not been any influence shown of the hull shape on the unconsolidated portion of ridge resistance. None can be established now either. However, it seems that the most important factor is the size of the hole made into the ridge as well as the amount of ice needing displacing to create this hole. This outweighs any influences of icebreaker bow shapes tested and evaluated so far.

#### 11.4. Turning performance

##### 11.4.1. General

Turning circle performance models are derived for the prediction of the influence of the reamers and of heel on steady turning performance in level ice. The full scale data supports development of these turning circle models for an index turning circle which is in ice 60 percent of the thickness of maximum continuous level ice breaking at 1 m/s.

It is not possible within the limited data set to develop a separate model describing the turning performance of the vessels without reamers. Only three of the vessels, Terry Fox, Ikaluk and Arctic Ivik are in this category and due to the limited data available a serious modeling process can not be carried out.

The one strong influence noted for these vessels is that

of the length of the parallel middle body. Arctic Ivik is however included in the data set for the reamer model since its geometry is similar to that of a reamer vessel with zero width reamer and chines.

#### 11.4.2. Parameters

The parameters to be incorporated into the turning circle model for reamer vessels are:

Level ice thickness for 1 m/s level ice breaking  
Reamer width  
Length of parallel middle body  
Length of waterline

The influence of the rudder configuration on the turning could not be established based on the full scale data plots, in Section 6. This is also accordingly left out in the basic turning model. It seems that the influence of the length of the parallel middle body for vertical sided ships with chined design, and the influence of the reamers are so clear that the influence of any other parameters on the turning can not be established based on calibration with full scale data.

The Parameters for the model to calculate the influence of heeling on the turning circle are based on the physical explanation to the influence of heeling. It has been established that the reason the heeling helps the icebreakers turn is mainly due to the fact that a side force is introduced to the bow. For an upright icebreaker both sides of the bow have approximately equal side forces and the only active force to turn the icebreaker is the rudder force. For a heeled vessel the asymmetry introduced to the bow region introduces at the same time unsymmetric force. Thus the turning is actively helped by the rudder as well as the new sideways force on the bow of the ship. The degree to which heeling helps icebreakers to turn in ice depends on the heel angle. This is understood by the increasing unsymmetry in the bow angles as a consequence to the increased heeling. The other factor which influences the magnitude of the side force on the bow when heeled is the design of the bow. High flare angles in the bow provide low initial side resistance. When the ship is heeled the difference in the side force therefore on port and starboard side is not very large either. When the section shapes are steeper the sideforce is increased in the bow region and at the same time the unsymmetric force in a heeled position. Based on the explanation above, the parameter selection beyond the parameters in the basic model is:

- heel angle
- flare angle



#### 11.4.3. Mathematical Models

The turning circle model is a result of a regression on the data in Chapter 6, Figure 6.2. The model gives for 60 % of level ice thickness at 1 m/s:

$$D/L_{wl} = 44.6 * 0.478(Br/Lp)$$

where D = turning circle diameter (m)  
L<sub>wl</sub> = waterline length of ship (m)  
Br/Lp = width of reamer, % of length of parallel midbody at waterline

The correlation coefficient for this model is 0.993 which essentially explains all the full scale data very well.

Figure 11.4.1. shows a parametric plot of the turning circle calculation and the full scale data incorporated into it.

The influence of the heel model is a result of a regression on the data in Chapter 6, Figure 6.3. The model gives the influence of the flare angle and the heel angle on the turning circle in the ice thickness of 60 % of level ice breaking at 1 m/s.

$$D_h/D_v = 1 + \text{heel}/6 * \cos(\beta - 180)$$

where D<sub>h</sub> = turning diameter, heeled (m)  
D<sub>v</sub> = turning diameter, vertical (m)  
heel = heel angle (degrees)  
 $\beta$  = average flare angle (degrees)

Figure 11.4.2. shows the influence plotted as well as the corresponding full scale data on the same graph.

#### 11.4.4. Discussion

The turning circle model giving the turning circle for ships with long parallel midbody and reamers seems to be a very accurate predictor of the turning circle judging from the good correlation with the full scale data and the mathematical expression for the turning circle. However, it should be remembered that the turning circle size is also dependent on the rudder angle for each of the ships in this study. Therefore it should be carefully established what the role of the rudder force in this respect is. The data correlation seems almost too good considering the differences between the efficiencies of the rudders.



The influence of the heel model is now based on two ships and within those hull configurations and ice conditions the model is accurate. The extrapolation of this model should not be considered beyond the hull shape parameters, because the influence of the unsymmetry of the hull shape when heeled is complicated and is not clearly established. The models should be treated with caution in this respect.

### 11.5. Open water performance

#### 11.5.1. Scope of model

The model calculates open water resistance representative for the Beaufort Sea icebreakers. All these ships, and the Max Waldeck have similarities in hull design which introduce chines and complications to the hulls causing an increased resistance in open water over a basic hydrodynamically designed hull. Thus it is considered that in this project the most appropriate model, which can be used to give the first indication of the level of open water resistance for similarly designed ships is this regression.

#### 11.5.2. Parameters

The parameters incorporated into the open water resistance model are:

- Power
- Displacement
- Length of waterline
- Ship speed

#### 11.5.3. Mathematical Model

The model is a regression line through the data in Figure 7.1. This gives :

$$R/Disp = 2.2 * [v/sqr(gL_{wl})]^2$$

where R = ship resistance (MN)  
Disp = ship displacement (tonnes)  
v = ship speed (m/s)  
g = gravity acceleration, 9.81 m/s<sup>2</sup>  
L<sub>wl</sub> = water line length of ship (m)

The result is given in Figure 11.5.1.

#### 11.5.4. Discussion

The model represents the full range of Beaufort Sea designs and is not accurate for any particular one of them. However, the use is perhaps best in comparing with other designs with more hydrodynamic preference in mind.

#### 11.6. Transit performance

##### 11.6.1. General

The model is based on full scale data of the transit with the Kigoriak in winter Beaufort Sea ice conditions. The Kigoriak has further transit data in thicker ice in spring (June) as shown in Figure 9.1. The scope of the transit model is set to explain the actual drop of ship speed from the level ice speed as a function of the density of ridging. The model only applies to the size and type of ship as the Kigoriak and Terry Fox. The thrust over displacement of another ship as well as the displacement should be about the same as for those ships in order for transit model to apply.

##### 11.6.2. Parameters

The model calculates the level ice speed and then the required ramming and influence of the environmental parameters on this and incorporates the following parameters:

- level ice thickness, winter
- speed in level ice
- speed in channel for impact
- number of ridges per kilometer requiring ramming
- summer, as equivalent winter ice thickness
- required amount of rams/kilometer

##### 11.6.3. Mathematical Models

The winter condition is used to develop the model and a correction is made to the model to account for the summer improvement of transit performance. It should be noted as well that the summer performance still only accounts for transit in a solid ice sheet, which has not broken into floes to any degree. A radical improvement of performance would be resulting from transiting in ice broken into any sizes of ice floes.

The basic mathematical model takes the starting point from January transit for the Kigoriak, which is the best documented one, and as summarized in Chapter 9. The number of rams/km of distance and the ridges requiring ramming/km gives

good match in January transit with the full scale data when the actual transit speed is compared against the level ice speed degraded by the ramming and assuming 200 second ramming cycles, as indicated in Chapter 8.

The influence of the increased ice thickness and density of ridges are taken into account in the followign ways:

- the decreasing ship speed in level ice means lesser speed available to penetrate ridges without ramming. This increases the number of ridges per kilometer which need to be rammed.
- the decrease of ship speed with increasing ice thickness decreases the penetration energy available from a ram. This means more rams are required per ridge.
- the increased ice thickness means increased ridge consolidation which means that the ridges require more energy to penetrate. This means more rams per ridge to penetrate.
- the number of ridges per kilometer when increasing increases the number of ridges requiring ramming.

For the above influences the development of dependencies is done in (APP). They are all based on the Kigoriak full scale dataon the perfromance in level ice channels and ridges as well as the transit data in January. The influences are:

- For increased number of ridges to be rammed with increasing ice thickness

$$N/N_{0.95} = (2 * H_1 - 1.22)/0.75$$

where N = number of rams in thickness  $H_1$   
 $N_{0.95}$  = number of rams in 0.95 m thick ice  
 $H_1$  = level ice thickness (m)

- Increase of number of rams per kilometer due to decreased ship energy.

$$N/N_{0.95} = (4.8 - 1.2 * H_1)^2 / 13.4$$

- Increase of number of rams due to increased consolidation.

$$N/N_{0.95} = 0.5 + 0.5 * (H_1/0.95)^{1.5}$$

An example is shown in Figure 11.6.1. on the calculated transit speed for the Kigoriak as a function of the ice thickness and density of ridges.

#### 11.6.4. Discussion

The validity of the models presented here is good for the Kigoriak, and is expected to be reasonable for the Kalvik. It also should apply reasonably for similar size and thrust ships provided that proper level ice performance data can be used as input for them.

A good check on the validity of the model is to check the actual transit performance of the Kigoriak in June against the method presented. There is an actual difference of performance the method predicting about 20 per cent faster progress for June than the actual. This could be attributed to the fact that the propulsion ice interaction is not taken into account. It is known from the Kigoriak data, as summarized in Chapter 8, that the propulsion ice interaction indeed takes an average of 15 - 20 per cent of ramming cycle time. Thus in June when the ice is very thick it is expected that the propulsion ice interaction could slow down the ships progress by this amount, or more because that is the very thick ice that the ship transits in June, and the propulsion ice interaction is at its worst in thick ice.

FIGURE 11.2.1  
INFLUENCE OF BUTTOCK ANGLE ON  
LEVEL ICE RESISTANCE

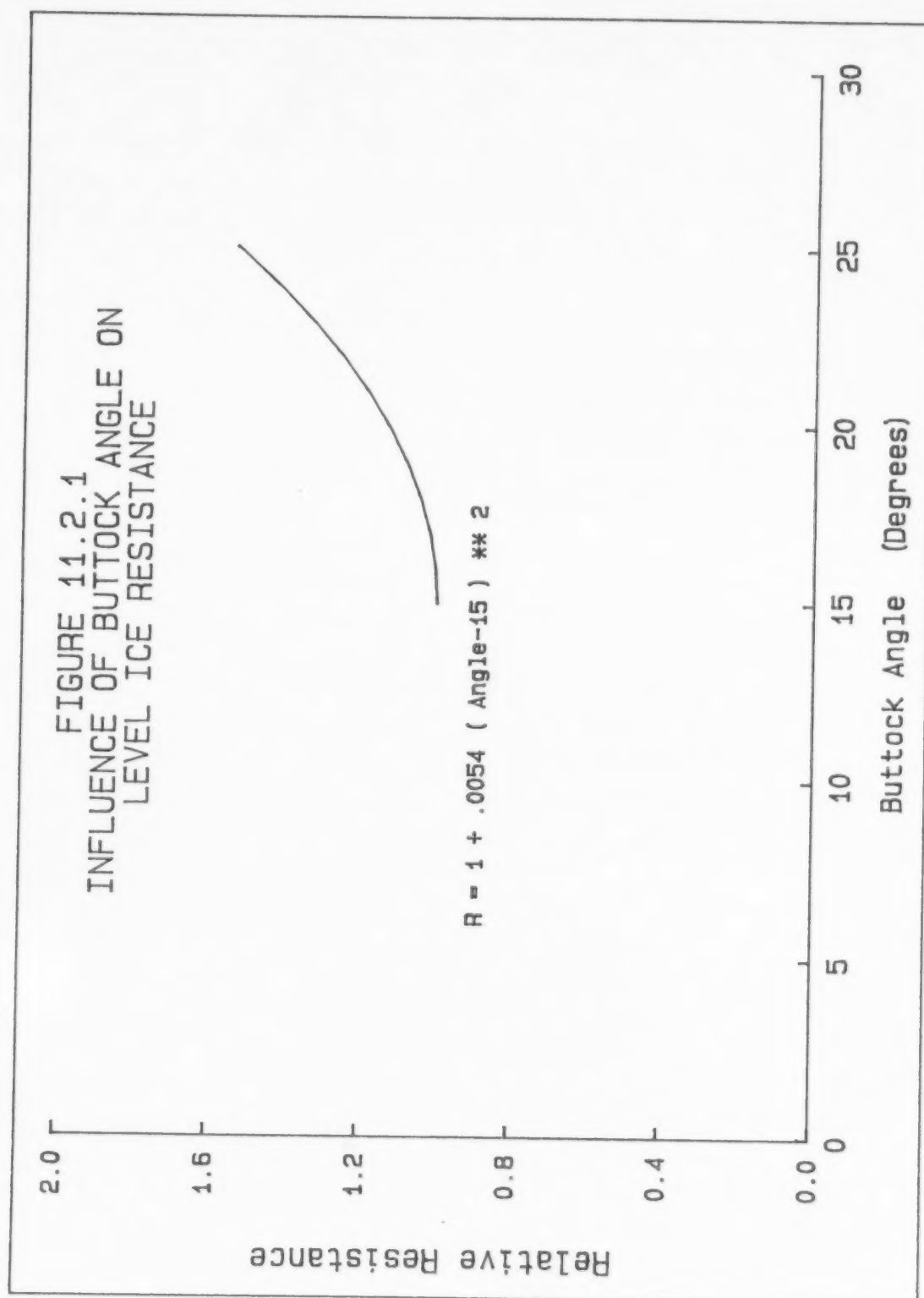




FIGURE 11.2.2  
INFLUENCE OF FLARE ANGLE ON  
LEVEL ICE RESISTANCE

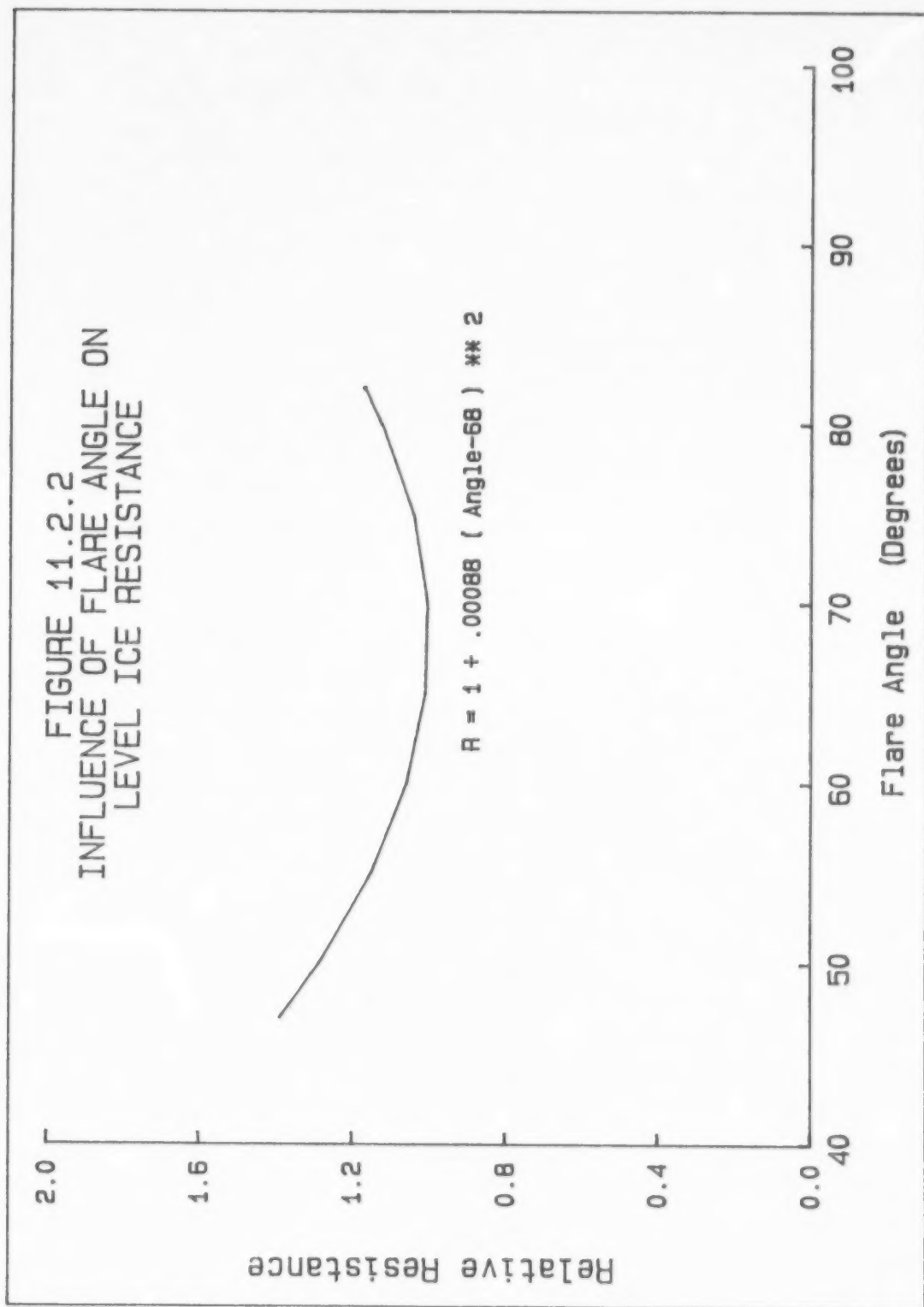


FIGURE 11.2.3  
LEVEL ICE RESISTANCE FOR  
REFERENCE SHIP  
Winter Ice

Level Ice Resistance

$$R = 0.43 * H ** 1.45 * (1 + .28 * (V - 1))$$

H = 0.9 m

H = 0.75 m

H = 0.5 m

Velocity ( m/s )

FIGURE 11.3.1  
CALCULATED SPEED OF ADVANCE THROUGH  
CONSOLIDATED FIRST YEAR RIDGES  
FOR REFERENCE SHIP

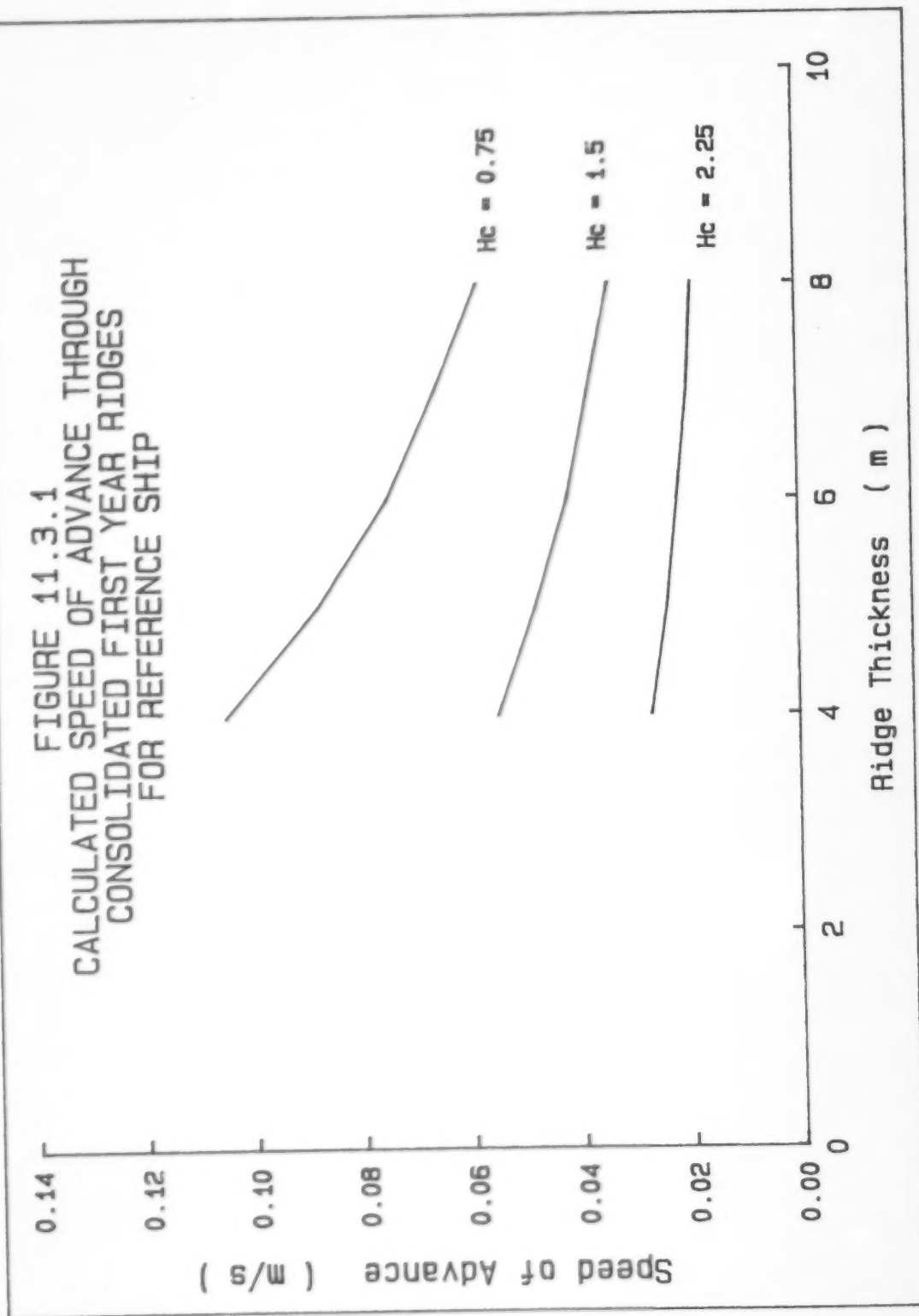
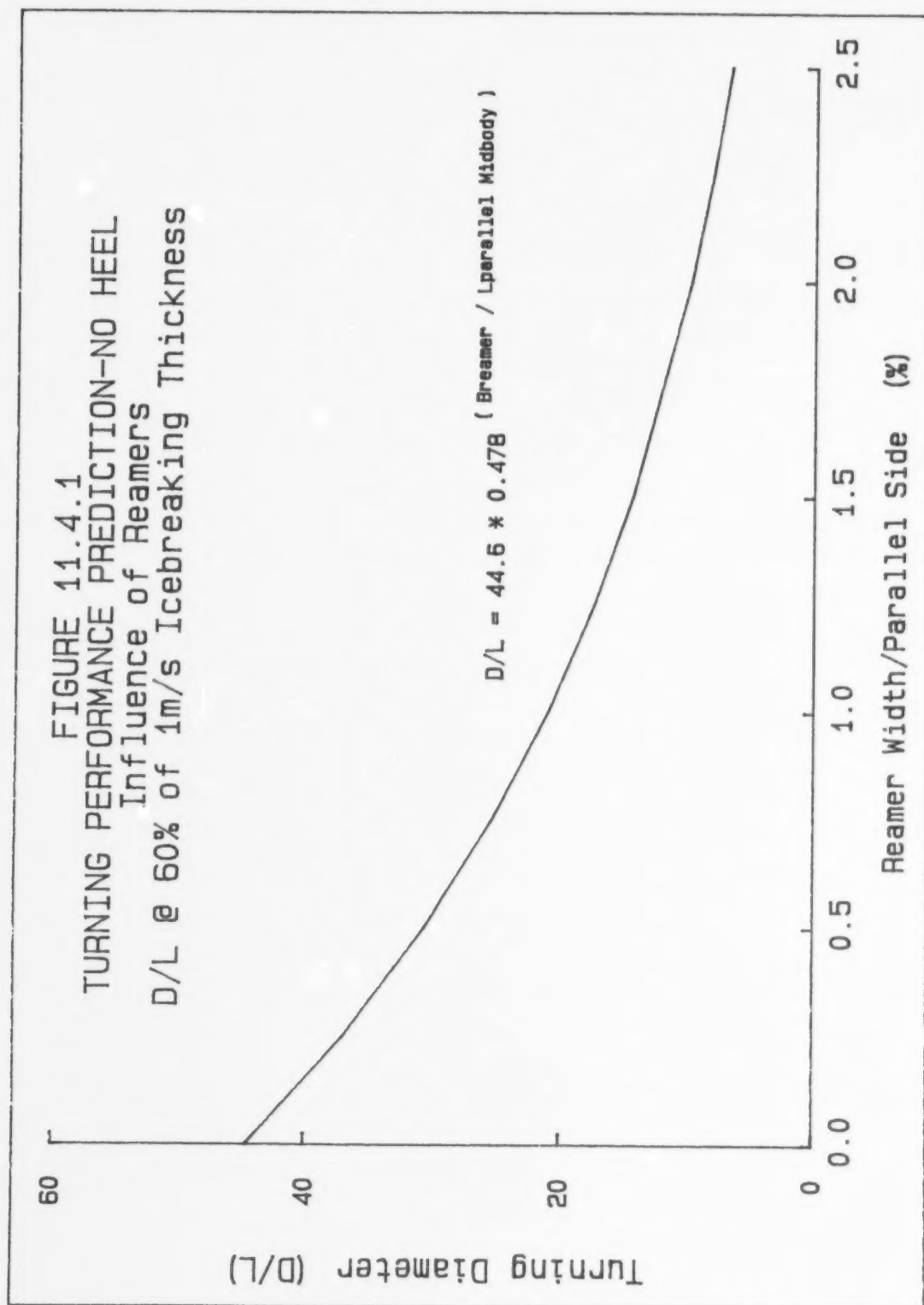


FIGURE 11.4.1  
TURNING PERFORMANCE PREDICTION-NO HEEL  
Influence of Reamers  
D/L @ 60% of 1m/s Icebreaking Thickness



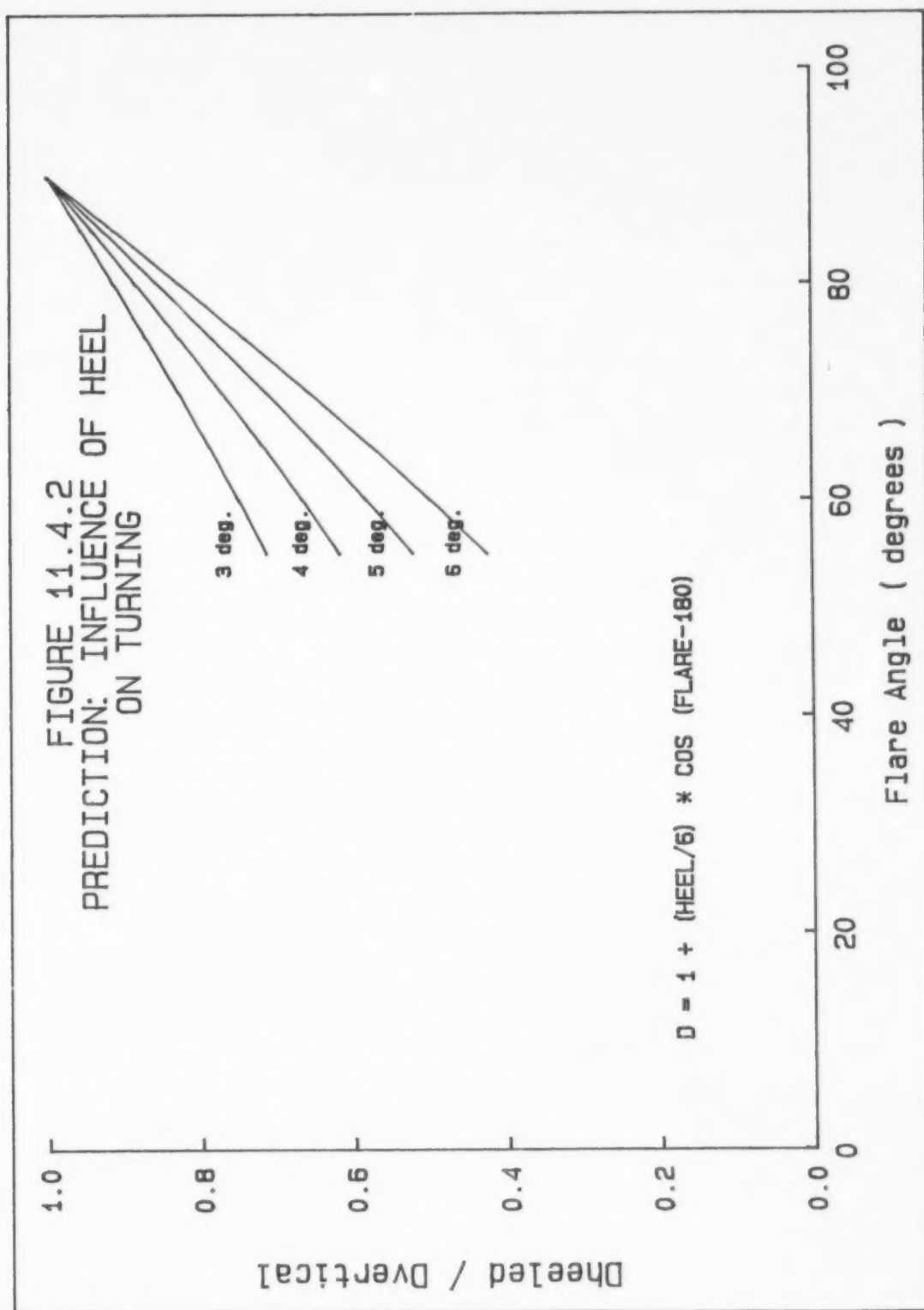




FIGURE 11.5.1  
OPEN WATER PERFORMANCE PREDICTION  
Resistance/Displacement vs Froude No.

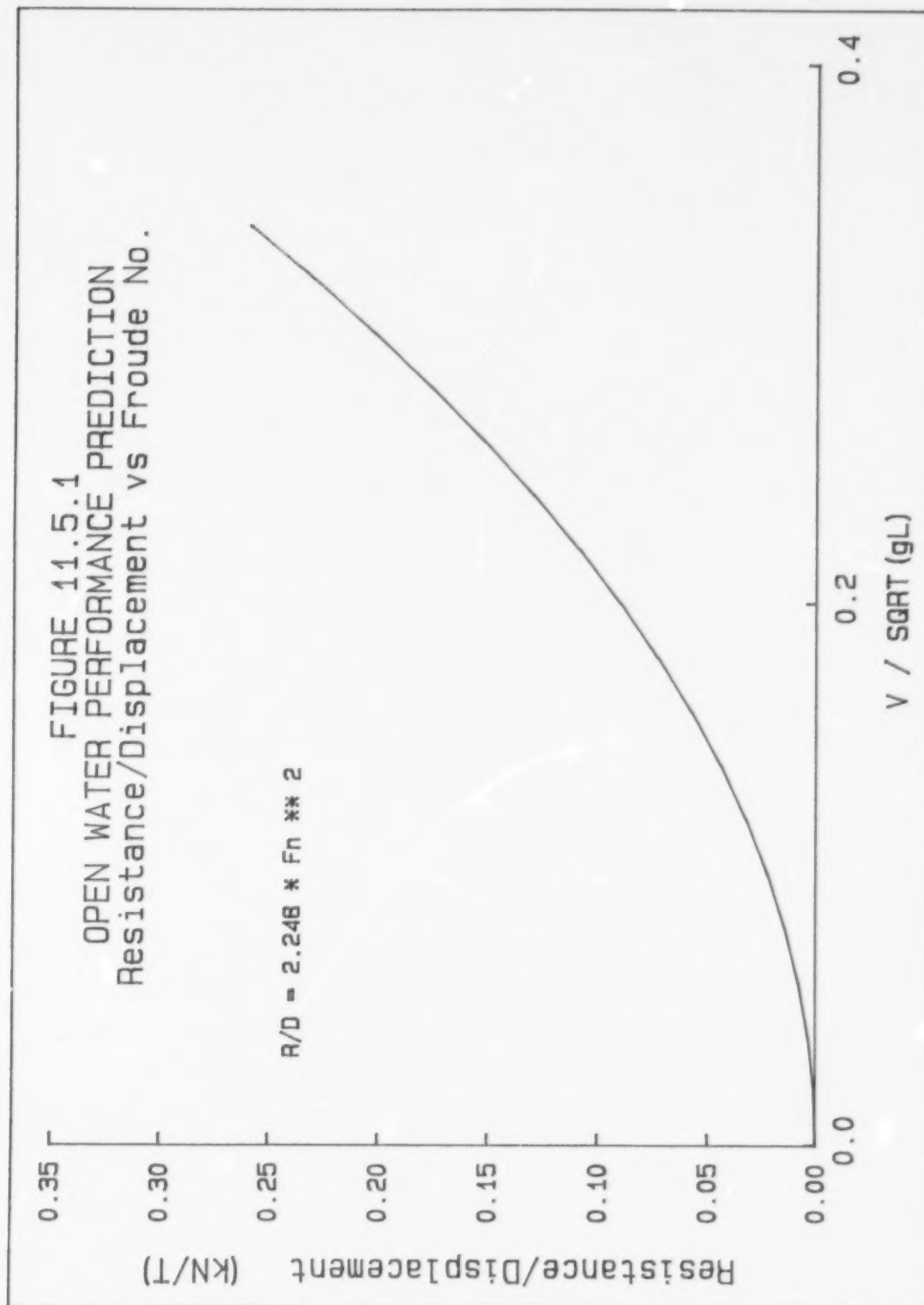
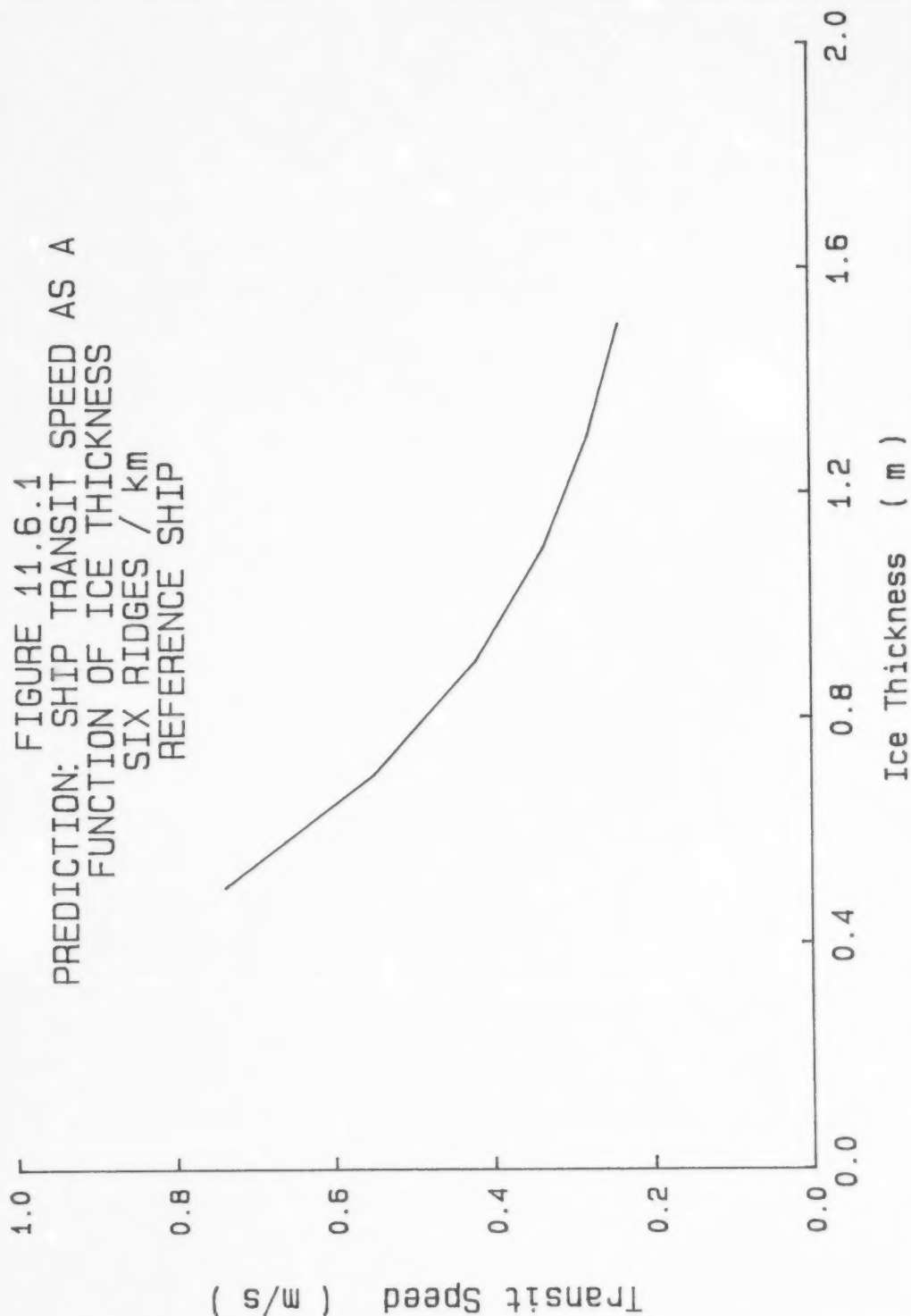
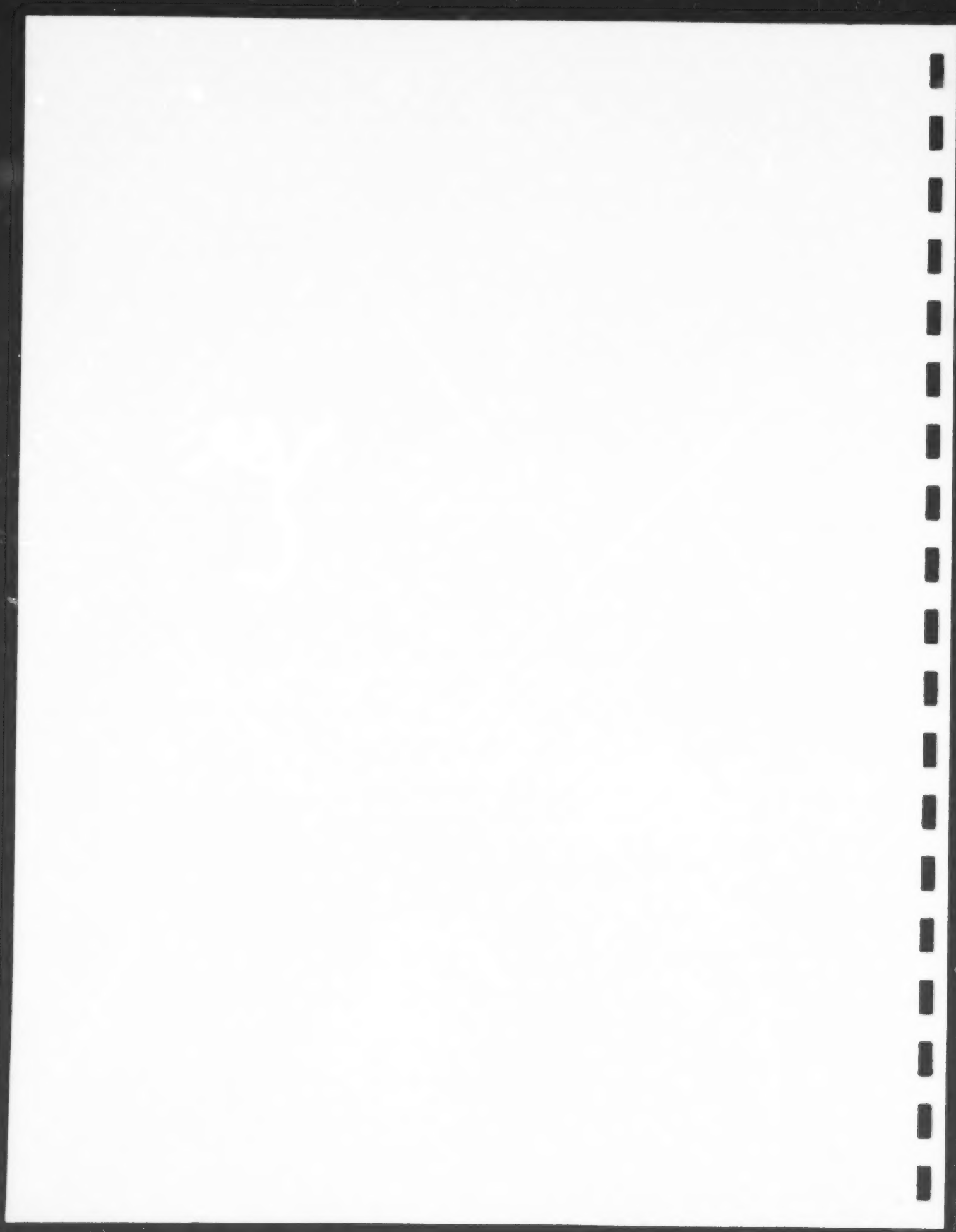


FIGURE 11.6.1  
 PREDICTION: SHIP TRANSIT SPEED AS A  
 FUNCTION OF ICE THICKNESS  
 SIX RIDGES / km  
 REFERENCE SHIP





## 12. CONCLUSIONS

### 12.1 Overview

The conclusions fall into two broad categories:

1. Specific results involving the performance of the vessels and their particular design features and the ability of the vessels to accomplish their mission roles.

2. Degree of success of methodologies undertaken in this project.

Figure 12.1 provides a schematic of the linking of the key elements in this project. In this report the full scale data has been analysed and parametric dependencies determined. The results from the data analysis have been used to build performance prediction models. The operator interviews have been analysed and information obtained in a qualitative sense on the role of the design features on the performance of the vessels while carrying out their mission roles.

The two streams are brought together in these conclusions to provide a practical set of designer and operator usable information.

### 12.2. Vessel Performance and Design Features

#### Bow

1. All Beaufort Sea Icebreakers and Max Waldeck have a low level icebreaking resistance.
2. The shallowest stem angles (buttock) and largest frame opening angles (flare) in the bow provide the lowest icebreaking resistance.
3. The advantage from the low buttock angles and high flare angles in the bow is partially lost at higher speeds of level icebreaking.
4. Based on Max Waldeck results the Waas principle of shearing the ice at the edges of the bow does not appear to offer advantages over Beaufort Sea technology in terms of level icebreaking performance. It has the second lowest ice resistance of all compared ships. Based on the influence of buttock angle on icebreaking resistance this could be mainly accounted for by its low buttock angle ( $16^{\circ}$ ) rather than the Waas principle of icebreaking by shear.

5. Judging from the low overall ice resistance there is no evidence that any of the wedges or chines of these icebreakers would have a major degrading influence on resistance in ice.
6. Bow forms with large flare angles and no centerline V shape tend to follow weakness in ice cover (cracks, thin ice).
7. The hull forms with large flare angles and small buttock angles tend to push ice straight down the bow and under the ship.
8. Large flare angles enable a ship to break out of a channel more easily.
9. The open water performance of these ships is not even close to more hydrodynamic shapes. The wedges under the bows, the chines and the reamers have contributed to the high open water resistance, 20 - 50 % above the fully developed traditional shapes.
10. The vessels with large flare angles tend to pound in waves to a greater extent.

#### **Bow Wedge**

1. Wedges are effective in clearing ice from the wake. They are less effective at higher speeds. The deep wedges extending to the ship's side are more effective than partial wedges.
2. For stopping in ridges and for effective ice splitting the wedge should not have a blunt waterline shape as the decelerations will be high.

#### **Reamer**

1. The main contribution measured from the reamers is a major improvement in turning capability ahead, for these icebreakers with long parallel midbody. Reamers can reduce the turning diameter by 60 - 80 percent of the turning diameter of one without them.
2. The data proves that the degree of improvement of turning is directly proportional to the width of the reamer, relative to the length of the parallel midbody.
3. There is no data or experience which shows any important drawbacks to reamers for operations in ice.



4. Reamers decrease midbody contact with ice in level ice and pressured ice conditions.
5. In heavy ridging the operators of all ships exercise caution when ramming ridges. This takes the form of widening the hole in heavy ridges before fully penetrating the ridge. This practice is carried out by the captains of both the reamered and non-reamered ships.

#### **Parallel Midbody**

1. Long parallel vertical sided midbody in Beaufort Sea icebreakers has led to a large turning circle in ice. Slight curvature of waterline and small side slope ( $8^{\circ}$ ) of the parallel side have given a somewhat improved turning capability. The reamers combined with straight vertical sides are much more efficient in reducing the turning circle to a reasonable size.
2. No data or experience indicates that there would be any other drawbacks to long chined parallel midbody in ice or in open water.

#### **Stern**

1. At full operating draft the square sterns of all Beaufort Sea Icebreakers result in the vessel having a considerably lower icebreaking capability astern relative to ahead. At a reduced draft the high resistance shapes are partially lifted out of the water and a somewhat improved astern performance is obtained.
2. Side cutaway of the square sterns offers good capability for breaking out of a channel astern.

#### **Propulsion Arrangement**

1. At normal icebreaking speeds nozzles consistently give considerably improved performance in icebreaking ahead over the open propellers due to increased thrust by the nozzle.
2. The open propellers give consistently a better astern performance and operator satisfaction in operations in heavy ice requiring astern operations.
2. The nozzles function satisfactorily without significant influence from ice interaction in the ahead mode of icebreaking.

3. The nozzles systematically cause major degradation of astern performance in channels due to blockage. In the ramming cycle performance at the initial start of the acceleration phase of a ram, blockage of nozzles degrades the performance in heavy ridging.
4. Based on this study controllable pitch propellers, whether open or nozzled, operate well in severe ice conditions.
5. Open screws generate a greater thrust than nozzled screws in conditions where the propeller is surrounded by ice (ridges and pressure). They are also capable of generating a greater effective thrust in broken channels astern.
6. The operators of open screw vessels exercise caution in multi-year ice to avoid blade damage. The operators of the nozzled screw vessels are far less concerned with this aspect of performance.
7. A skirt around the nozzled propellers is capable of eliminating most of the blockage. This is achieved at the cost of substantially increasing resistance astern, as well as a likely compromise in propulsion efficiency in open water.

#### **Friction Reduction Devices**

1. The hull lubrication system pumping water onto the ice ahead of an icebreaker is by far the most efficient friction reduction device investigated in this study. It gives in most level ice operations a power saving on the propellers several times the power it uses itself.

#### **Hull Coating**

1. The quality of the hull surface influence ice resistance in a major way. Inerta coating in comparison with bare steel gives a 25 % reduction in ice resistance. A rough hull surface will cause an increase of resistance in the order of 40 % over the bare steel. The overall increase of ice resistance from an Inerta coated hull to a rough steel hull can be as much as 86 %. This points out the very important aspect of keeping an icebreaker hull well coated with an effective low friction hull coating.

### **12.3 Methodologies**

#### **12.3.1 Interview**

1. The results of the interview agree with all the full scale data trends.
2. In addition the results from the interview provide performance information that is not available from the limited scope full scale trials.
3. The results provide information on the performance compromises of some of the design features when the vessels are used in their actual mission roles as opposed to testing in the somewhat idealised conditions which occur during trials.

#### **12.3.2 Data Analysis**

1. The analysis of the data permits a unique comparison of the performance of the vessels in the various performance categories by putting the data on a common data base.
2. The analysis shows some of the key influences of design parameters and features on specific performance categories. The results are limited by the range of parameters of the vessels in this study and the extent of test data available.

#### **12.3.3 Models**

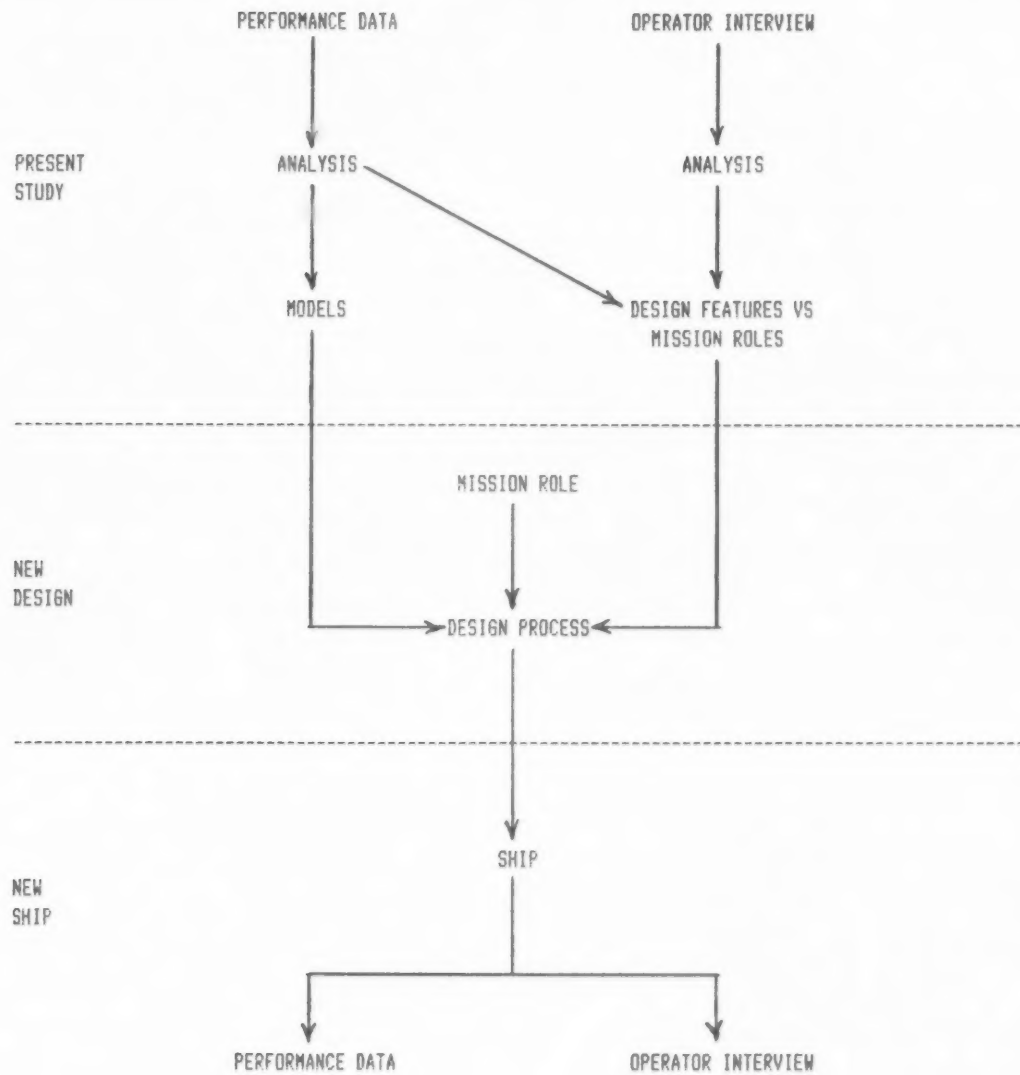
1. The models provide the designer with a tool to predict the performance of a vessel in several performance categories. The models are valid for different combinations of design features covering any values within the range of design features applicable to the study. The models are based on and calibrated with full scale data.

#### **12.3.4. Overall Methodology**

1. The process of combining the interview and data analysis in a single project has proven highly successful. The interview data complemented the limited amount of full scale data giving an opportunity to make an overall evaluation of the vessels and their design features.

FIGURE 12.1

USE OF STUDY IN DESIGN PROCESS



### 13. RECOMMENDATIONS

The recommendations resulting from this project fall into two categories; the use of the present study and future work beyond the scope of the present study to increase the usefulness of the results for the designer.

#### 13.1 Use of the Present Study

1) By use of both the models and the understanding of the role of the individual design features in determining the performance, the designer can select the type of design feature that best meets the needs of the mission roles for a new ship (subject to working within the applicable range of parameters in this study). This is illustrated in figure 12.1. This can be done with confidence as the results of this study are based on full scale data in well documented ice conditions.

2) The designer can use the results of this study to compare the performance of the ships in the study with other ships with which he is familiar, providing that the other ships are corrected to an equal data base to enable a valid comparison.

#### 13.2 Further Development of the Methodology

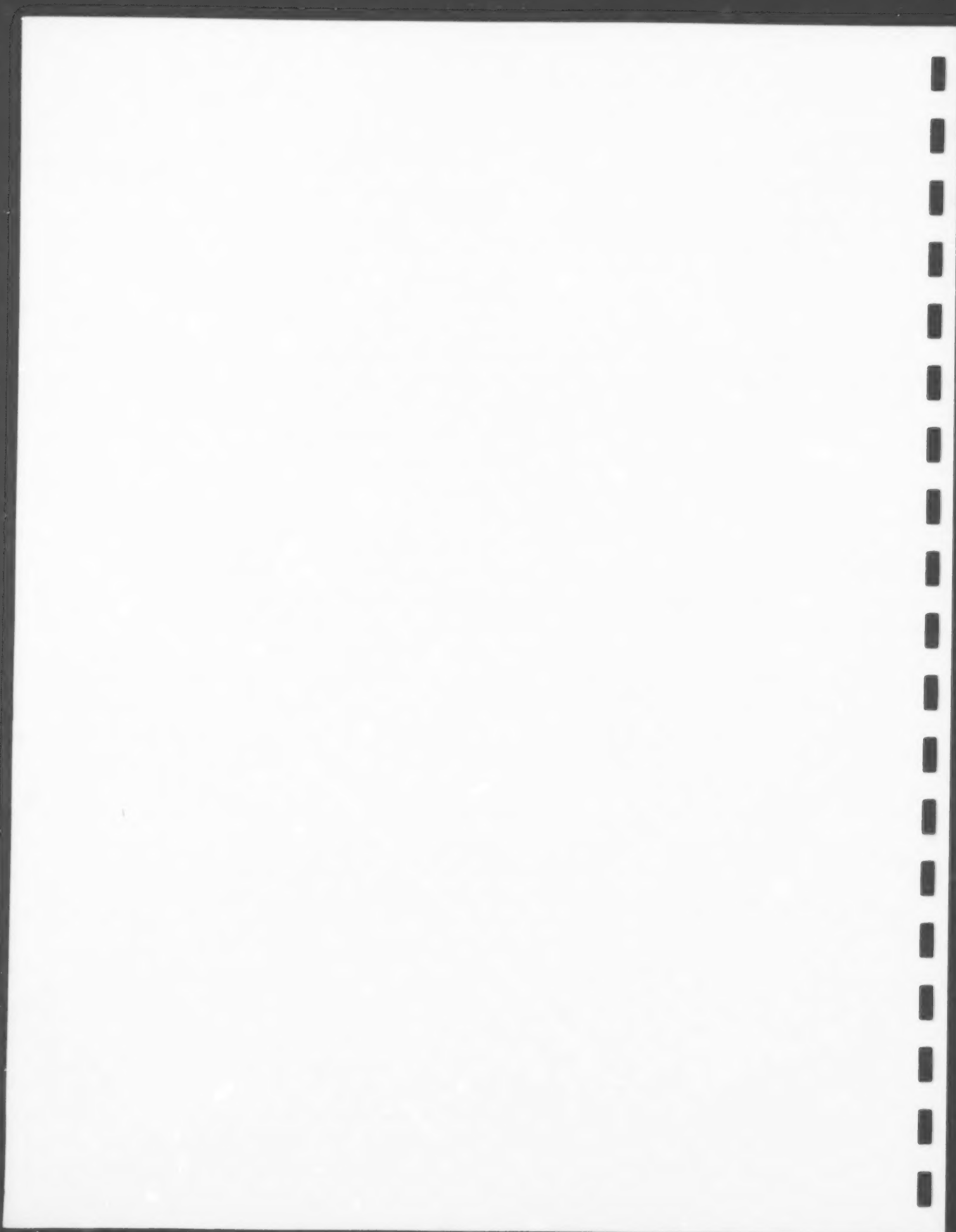
1) The range of parameters should be extended by incorporating the results from additional tests and interviews. This will utilise both existing data and should incorporate new data as it becomes available. (See figure 12.1). This will enable a comparison of the present ship features with other design features outside the present range of parameters and will introduce new features beyond the present scope.

2) Good environmental data must be collected and documented in full scale tests to enable a valid comparison between different tests.

3) The effects of ice strength on resistance should be determined from well documented full scale trials of similar ships. This should enable performance data to be corrected to a common ice strength.

4) Common procedures and methodologies should be carried out during full scale testing. As a minimum the test procedures should be well documented.





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